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Strength grading of hardwoods for glulam application. Mechanical properties and quality control options

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Abstract

Hardwoods are very well known to have superior mechanical properties for structural applications. However, until now, the full potential of hardwoods has not been exploited, as compared to softwoods, fewer fundamentals on material performance in structural dimensions and processing are available. The current thesis deals with the strength grading of hardwoods as one of the major processing steps on the way to superior products, such as glulam.

The thesis covers multiple topics. First, the relationships between the mechanical properties are analysed for the medium-density European hardwoods to provide feasible relationships as a basis for the design and strength grading. Second, different strength grading methods and potential methods are analysed regarding their potential for structural applications. By using the derived profiles, applying the grading methods and optimizing the grading rules, finally, the characteristic properties of the medium-density European hardwoods are assessed. The thesis covers, furthermore, the different quality control options to guarantee the mechanical property values and the economic feasibility of lamella production from hardwoods.

For the current thesis, overall, 4682 hardwood test data from different loading modes after EN 408, over 4158 softwood test data, and 279,235 grading machine readings of spruce were used. Multiple of the boards were visually assessed regarding local defects, particularly knots, and various state-of-the-art machine grading methods, as well as transverse ultrasound scan - a potential method for wood strength grading - were analysed.

Zusammenfassung

Laubholz ist für seine hervorragende mechanische Eigenschaften bekannt. Allerdings wird das volle Potenzial von Laubhölzern bisher nicht ausgeschöpft, da für sie im Vergleich zu Nadelhölzern weniger Grundlagen für die Anwendung im konstruktiven Bereich vorliegen. Die Abschlussarbeit befasst sich mit der Festigkeitssortierung von Laubhölzern als einem der wichtigsten Verarbeitungsschritte auf dem Weg zu den hochwertigen Produkten wie Brettschichtholz.

Die Untersuchung umfasst mehrere Themen. Zunächst werden die Beziehungen zwischen den mechanischen Eigenschaften für die mitteldichte europäischen Laubhölzer analysiert, um mögliche Beziehungen als Grundlage für die Bemessung und Festigkeitssortierung bereitzustellen. Zweitens werden unterschiedliche Verfahren der Festigkeitssortierung, sowohl die etablierten als auch die neuartigen auf Basis des Ultraschalls quer zu den Fasern, hinsichtlich ihres Potenzials für strukturelle Anwendungen analysiert. Unter Verwendung der hergeleiteten Festigkeitsprofile, Anwendung der Sortierverfahren und Optimierung der Sortierregeln werden schließlich die charakteristischen Eigenschaften der mitteldichten europäischen Laubhölzer ermittelt und bewertet. Darüber hinaus werden die verschiedenen Möglichkeiten der Qualitätskontrolle zur Gewährleistung der mechanischen Kennwerte und der Wirtschaftlichkeit der Lamellenherstellung aus Laubhölzern untersucht.

Für die vorliegende Arbeit wurden Testdaten von 4682 Prüfkörper aus Laubholz, geprüft unter verschiedenen Belastungsszenarien nach EN 408, und 4158 Fichten Zug-Testdaten und 279.235 Sortiermaschinen-Messwerte von Fichte verwendet. Mehrere der Bretter wurden visuell auf lokale Fehler, insbesondere Äste, beurteilt und verschiedene hochmoderne maschinelle Sortierverfahren, darunter bildgebendes Verfahren auf Basis des Ultraschalls quer zu den Fasern - potenzielles Verfahren zur Festigkeitssortierung von Schnittholz -, wurden analysiert.

Publications

I. **A. Kovryga**, P. Stapel, and J. W. G. van de Kuilen. Mechanical properties and their interrelationships for medium-density european hardwoods, focusing on ash and beech. *Wood Material Science & Engineering*, 88(6):1–14, 2019.

II. **A. Kovryga**, P. Schlotzhauer, P. Stapel, H. Militz, and J. W. G. van de Kuilen. Visual and machine strength grading of european ash and maple for glulam application. *Holzforschung*, 73(8):773–787, 2019.

III. **A. Kovryga**, A. Khaloian Sarnaghi, and J. W. G. van de Kuilen. Strength grading of hardwoods using transversal ultrasound. *European Journal of Wood and Wood Products*, 78(5):951–960, 2020.

IV. **A. Kovryga**, J. O. Chuquin Gamarra, and J. W. G. van de Kuilen. Strength and stiffness predictions with focus on different acoustic measurement methods. *European Journal of Wood and Wood Products*, 78(5):941–949, 2020.

V. **A. Kovryga**, P. Stapel, and J. W. G. van de Kuilen. Quality control for machine strength graded timber. *European Journal of Wood and Wood Products*, 75(2):233–247, 2017.

VI. P. Schlotzhauer, **A. Kovryga**, L. Emmerich, S. Bollmus, J. W. G. van de Kuilen, and H. Militz. Analysis of economic feasibility of ash and maple lamella production for glued laminated timber. *Forests*, 10(7):529, 2019.

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1 Introduction

1.1 Overview

In the course of history, wood always gained in attractiveness as a building material. In recent history the softwoods have been the focus of production on both the producer and customer side. Short rotation period, large availability and attractive prices have led to a large domination of softwoods in the building sector. Nevertheless, in recent decades, the application of hardwoods for constructive purposes has gained popularity. Both research and practice are collaborating to create markets as the broad-leaved forestry stocks in Europe are growing. As reaction to the global climate change and sustainable development, the forestry policies changed, promoting a higher share of hardwoods in European forests. However, to sustain this development, new markets for hardwood resources are necessary. Despite the high availability of hardwood resources, the key markets able to utilize the exceptional visible and mechanical qualities of wood are missing. For example, in Germany, over the last decades the use of sawn hardwood products has even decreased. Novel products such as beech Laminated Veneer Lumber are an exception and remain a niche product, despite their excellent properties.

1.2 Hardwood resources

Of 215 million ha of forestry area in Europe, 36% is covered predominantly with hardwoods and 19% are mixed stands (Forest Europe, 2015). The highest percentages of predominantly broad-leaved stands are mainly located in Mediterranean countries and South-West and South-East Europe and countries under the oceanic influence in Central-West Europe. The higher percentages of mixed forests are located in Central-West Europe and represent 31% of the forests there (Forest Europe, 2015).

The hardwood stocks in Europe comprise multiple species. Dependent on the geographical area different wood species are predominant. In Southern part of Europe, species such as oak and chestnut are widespread, whereas in Northern Europe birch is a predominant hardwood species. In Central Europe, species like oak and beech are the most important ones. Beech is one of the most important hardwood species in Central Europe accounting for 15% of forest area in Germany (BMEL, 2015), 18.1% in Switzerland (BAFU, 2015), and 9.6% in Austria (Hausegger, 2017). Furthermore, there is a variety of hardwood species with rather small forestry areas. However, those species are gaining in attractivity due to the changing climatic conditions, as a potential substitute or addition to the softwoods.

In Europe, the growing stock of broad-leaved tree species amounts to 15.0 billion m^3, compared to 20.0 billion m^3 for softwoods. Between 1990 and 2015, the growing stock of broad-leaved trees accumulated at a higher rate compared to the growing stock of coniferous trees (1.6% and 1.2% each year).
The stronger growing hardwood stock clearly reveals the discrepancy between the available resources and the actual hardwood usage.

1.3 Mechanical properties of European hardwoods

Temperate European hardwood species cover a broad range of species with different biological structures, densities, and corresponding mechanical properties. Species such as poplar or chestnut generally show low mechanical property values (Aicher et al., 2014) and can be classified using regulations for softwoods to C- and T-Classes. Species with densities in the middle of the density range (550-850 kg/m^3), such as ash, beech and maple can be assigned to higher strength classes. Those species are known for their excellent mechanical properties (Kollmann and Côté, 1968).

In the following, an overview is given of the species primarily studied in this thesis. The studies on the mechanical properties of temperate European hardwoods, such as ash, beech, oak and maple reflect high property values for both tension and bending applications. Studies by Frühwald and Schickhofer (2005); Glos and Torno (2008a); Van de Kuilen and Torno (2014) for specimens tested in bending and tension and by Van de Kuilen et al. (2017) tested in shear report high mechanical properties of medium-density European hardwoods, such as ash and beech in structural dimensions.

Currently, the only available classification for ash in Europe is the visual grading in accordance with German visual grading standard DIN 4074-5. The ash lamella graded to the highest visual grade (LS13) can be assigned to the bending strength class D40 defined using the bending strength and MOE (EN 1912, 2012). For this class, the characteristic tensile strength of 24 MPa is defined on the safe side with mean MOE of 13 GPa. Currently, there are only existing assignments of the visual grades to the tensile strength profiles available to the softwood.

Both Norway maple (*Acer platanoides L*) and sycamore maple (*Acer pseudoplatanus L*) are common species in Europe for appearance applications. The potential of maple, particularly red maple (*Acer rubrum*), for structural applications has been studied primarily in Northern America where large stocks are available (Manbeck et al., 1993). The study by Green and McDonald (1993b) indicates high mechanical property values of red maple structural timber compared to softwoods. Selected structural (SS) – the highest strength grade in accordance with standard grading rules (NELMA, 1991)

shows the characteristic tensile strength of 32.0 MPa and mean MOE of 13 GPa tested over the free length of 1.5 m. Regarding the GDP ratios, already this result indicates possibly different f_t to E_t ratio compared to softwoods.
The use of maple for structural applications is less studied in Europe. Currently, for maple, no sophisticated classification system is available for the production of high-quality lamella similar to the European beech or red maple in the USA. Maple from Germany graded in accordance with the German visual grading standard DIN 4074-5 to LS13 can be assigned according to EN 1912:2012 to D30 with the characteristic tensile strength of 18 MPa and $E_{0,mean}$ of 11 GPa (EN 338, 2016). The MOE values are comparable to the values of the inner red maple glulam beam laminations (Manbeck et al., 1993).
While some information on the mechanical property values is available for ash and maple, the grading of the specimens is not optimized for the application in glulam. For beech, the optimized classification for the high-quality lamella exists and is dated back to Frese and Blaß (2007). The system includes requirements on the dynamic modulus of elasticity E_{dyn} for the high-quality boards. No classification system tailored to the mechanical property values of ash or maple is available. The mechanical properties reported by Van de Kuilen and Torno (2014) were estimated on medium-sized specimens, as the boards were tested with very short testing length of 200 mm in order to obtain data for the Karlsruher Rechenmodel for Glued Laminated Timber calculations as was done for European beech in Blass et al. (2005).

Glulam made from temperate European hardwoods shows high mechanical properties compared to softwood glulam. Ash and beech show load-bearing capacities exceeding 47.9 MPa (Frese and Blaß, 2007; Van de Kuilen and Torno, 2014; Ehrhart et al., 2018). Also, for other hardwoods such as oak, chestnut (Aicher et al., 2014) and birch (Jeitler et al., 2016) superior mechanical property values are reported. In a series of tests Manbeck et al. (1996) report characteristic bending strength of the maple glulam of as high as 36 MPa and of the mean bending MOE of 12.4 GPa. The engineered wood products are necessary to create a new market for lower-quality hardwood resources.

Manbeck et al. (1993) and Janowiak et al. (1995) report the feasibility of using red maple for glulam application and designed beams with low-grade inner lamella and high-grade outer lamella allowing efficient utilization of hardwood resources. To enhance the use of the wood resources, low-quality lamellas from inner log zones (containing pith) can be used to produce glulam beams with the same/similar design values as in the case of pith-free lamella (Janowiak et al., 1997). Chui and Delahunty (2005) report the economic and technical feasibility of producing glulam and high-capacity I-beams also for Canadian-grown red maple.

1.4 Strength grading

1.4.1 Timber strength grading

The research on hardwoods aims to utilize non-destructive methods already applied to softwood strength grading. However, the performance of the methods differs due to the species-specific characteristics on the microscopic and macroscopic scale. For strength grading of timber, different grading methods are used, generally distinguishing between visual and machine grading.

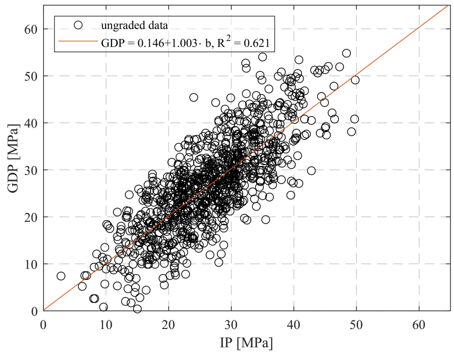
The major principle behind the strength grading is to split the population of ungraded timber into strength classes, with defined mechanical property values. Splitting the population into the grading classes allows to reduce the variation of the material and achieve higher strength values (e.g. Figure 1.1(d)).

The strength classes, as listed in Europe in strength class system of EN 338, comprise material profiles with defined mechanical properties. The strength class system includes bending strength classes for softwoods (C-Classes), tensile strength classes (T-Classes) and bending strength classes for hardwoods (D-Classes). The C- and D-Classes are defined based on the edgewise bending tests and T-Classes are defined based on tension tests.

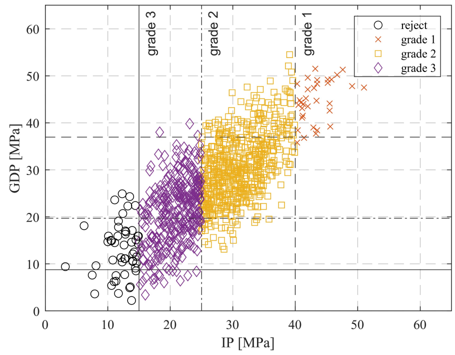
For the assignment of a sample to the strength class, the so-called 'grade determining properties' (GDP) are used. Those are the major properties that are obtained in a laboratory test. For bending C and D strength classes those are the bending strength, modulus of elasticity (MOE) and density. For tensile strength classes (T-Classes), the GDP are the tensile strength, MOE and density. Other properties comprising the material profiles are the so-called derived properties and are either listed in the strength class system or can be calculated using underlying equations of EN 384. Those equations include bending strength for tension strength classes and tensile strength for bending strength classes, compression strength parallel and perpendicular, tensile strength perpendicular to the strength and shear strength.

To assign a single timber piece to the strength class, the so-called 'indicating properties' (IPs) are used. Those properties stay in a certain, statistically defined relationship to the GDP and are measured non-destructively. Figure 1.1(a) shows the relationship between IP and GDP. This relationship allows to predict the mechanical property values. To assign the specimens to a certain grade, the population is split into classes based on thresholds applied to the IPs (Figure 1.1(b)). Figure 1.1(c) shows exemplarily the population split by thresholds of IP and Figure 1.1(d) shows the pdf of the f_t. The thresholds are also called machine settings and are determined using statistical procedures of EN 14081-2 and EN 14081-3.

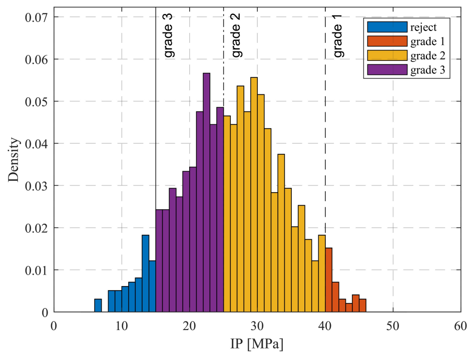
IP can refer to a single property, for example the dynamical modulus of elasticity, or the knottiness, or it can comprise several grading criteria in a multiple regression



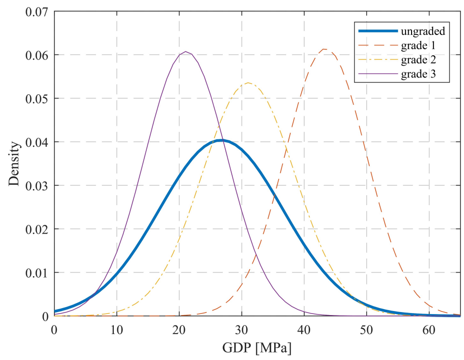
(a) Scatter plot IP vs GDP



(b) Scatter plot IP vs GDP



(c) Histogram of IP split into three classes



(d) PDF of GDP

Figure 1.1: Grading of a population into three classes: (a) Relationship between the indicating property and grade determining property; (b) Splitting the population into three classes based on the value of IP; (c) Histogram of IP values split using thresholds/machine settings and (d) Grading - splitting the population to the grading classes - grade 1, grade 2 and grade 3

model. In this case for the modeled strength (f_{mod}) is usually denoted as IP MOR or IP f_t. Dependent on the machine type, several IPs can be used, one for the each of the GDP (strength, MOE and density).

1.4.2 Visual grading

Traditionally, the sawn wood is graded visually. The visual grading standards define a number of the visible criteria used to assess the timber quality for structural applications. Most of the national grading rules (such as German visual grading standard DIN 4074-1 and DIN 4074-5 or British standard BS 4798), use such criteria, as knots, fibre deviation and the presence of pith to assign timber to certain visual grades. Based on extensive testing campaigns, mechanical property values are assigned to those grades. Generally, high correlation between knottiness and tensile strength can be reported for various hardwood species (Frühwald and Schickhofer, 2005; Ehrhart et al., 2016a). The R^2 values between knottiness and tensile strength range between 0.4 and 0.6 for beech and ash (Glos and Lederer, 2000; Van de Kuilen and Torno, 2014; Frühwald and Schickhofer, 2005; Ehrhart et al., 2016a). Despite the high R^2 value, the knots are severe in hardwoods compared to softwoods, as can be observed in Frese and Blaß (2007) and Ehrhart et al. (2016a) on European beech. This makes other criteria, such as fibre deviation, more relevant to address the quality of timber as well.

The fibre deviation is defined as an aberration of fibres from the loading direction over a certain length and is measured in % (grain deviation). The fibre deviation occurs locally as the wood fibres envelop the knots and globally as an angle to the longitudinal board axis and in specific cases such as spiral or cross grain. The grain angle has a significant impact on the strength (Hankinson, 1921). Most grading standards indicate that the fibre deviation can be measured on drying cracks or by the scribbling method on the wood surface. Both methods are reported to have limited use for medium-density hardwoods mainly because of indistinct or unclear fibre orientation and local fibre deviations (Glos and Lederer, 2000; Frühwald and Schickhofer, 2005). Ehrhart et al. (2016b) applied a more differentiated approach and rejected the fibre deviation for the high-quality beech lamella if visually observable.

Other criteria have rather minor effects on the mechanical property values, but pith could result in lower strength as boards with pith will have a higher content of juvenile wood. Visual grading also includes geometrical criteria such as wane or mechanical damages that reduce the cross-sectional area, rather than the mechanical property values.

1.4.3 Machine grading

Machine strength grading was first introduced around 1960 (Galligan and Devisser, 2004). The term machine grading means that timber is graded using machines, which leads to higher accuracy and repeatability compared to visual grading. During history, different grading machine types have been used for grading purposes. These grading types comprise a variety of parameters used for the quality assessment. Some grading machines are able to capture the visual quality of timber allowing to determine the weakest section that reduces the structural performance of the timber. In this case, either visual grading performed by the machine, or machine grading with an IP based on visual parameter is possible. Most common is, however, the use of non-visible grading criteria, such as density or dynamic MOE to grade timber. Moreover, some of the machines are deflection type machines which determine the static MOE of the board by measuring the deflection for a certain force or measuring the force required for a pre-defined deflection.

Density is one of the easiest to measure criteria to predict the mechanical properties of timber, but density as a single criterion shows low correlation ($R^2 < 0.1$) to strength for a number of hardwood species (Solli, 2004; Frühwald and Schickhofer, 2005). For hardwood species like ash, beech, oak, red maple the dynamic MOE shows low prediction values for the strength compared to softwoods with R^2 values below

0.2 (Ravenshorst, 2015; Frühwald and Schickhofer, 2005; Green and McDonald, 1993a; Van de Kuilen and Torno, 2014). For low quality beech Westermayr et al. (2018) report higher correlation ($R^2 = 0.51$). It should be noted, that, if graded independent of the wood species, the dynamic MOE shows moderate to high prediction accuracy of the strength in terms of coefficient of determination (Ravenshorst, 2015). Ravenshorst (2015) reports for temperate hardwoods R^2 values of 0.38 and 0.7 for the combination of softwood, temperate hardwood and tropical hardwood species. Enlarging the variation in measured dynamic MOE values allows establishing a numerical relationship between both variables. It should be noted that the dynamic MOE shows limited prediction performance for the strength as it evaluates only an average quality over the entire length of the measured specimen.

The prediction level for the static MOE using dynamic MOE is moderate to high. The reported R^2 range from 0.37 (Van de Kuilen and Torno, 2014) to 0.7 for ash (Frühwald and Schickhofer, 2005), 0.72 for red maple (Green and McDonald, 1993a) and 0.84 for beech (Ehrhart et al., 2016a). The low correlation in case of Van de Kuilen and Torno (2014) is a result of different gauge length for the MOE measurement. The length for MOE determination was only 150 mm as measurements were performed for the 'cell' length in the Karlsruher Rechenmodel for glulam, as done for beech (Blass et al., 2005). This distance accounted for by far fewer abnormalities affecting the MOE compared to the full length of the board (5 m) used for the dynamic MOE measurement. A single approval available for machine-graded timber in Europe is issued for chestnut timber classified using longitudinal vibration measurement (Brunetti et al., 2014).

Beside the non-visible criteria, machine grading aims to incorporate the local strength reducing criteria such as the knots and/or the fibre deviation into the prediction models. For softwoods, multi-sensor systems are able to combine the information on the weakest spot with properties indicating an average quality of timber. Machines combining the knottiness, density and vibration measurement are able to achieve R^2 values of as high as 0.69 for softwoods (Bacher, 2008). The common way to detect the knottiness is the X-ray attenuation measurement. By indicating the difference in X-ray propagation on clear wood and much denser knots, the position and size of these weak points can be measured (Giudiceandrea, 2005). This technique performs well for softwoods due to the high-density contrast between the knot and clear wood. The knots are double as dense as the clear wood. For hardwoods, the low difference between the knot and clear wood leads to less accurate knot detection if the same detection algorithm is used. To the knowledge of the authors, studies of the knot detection on hardwoods using X-ray attenuation are few. Nocetti et al. (2010) report for chestnut timber only of small prediction strength in terms of R-Squared value of 0.083 between the machine knottiness parameter and the bending strength.

Besides X-ray propagation, other non-destructive techniques for defect detection have been studied. A technique based on ultrasound wave propagation transversal to the grain direction (Schmoldt et al., 1994; Schafer et al., 1999; Fuller et al., 1994; Kabir et al., 2003) or thermal conduction properties of wood (Daval et al., 2015) shows a potential for the knot detection in hardwoods. However, for now, none of the methods has been industrially applied. In the FP7 European Project 'Woodsonic' a prototype machine was developed, but never brought to production due to the difficulties in the wave transmission between the sensor and wood.

The machine detection of the fibre deviation by means of different non-destructive techniques has been recently studied. For softwoods, the multi-sensory systems able to detect the fibre deviation by means of tracheid effect are available. Until recently, the information has been used for appearance grading only; the algorithms for strength grading are present (Olsson et al., 2013) and show promising results. Although hardwoods have different cell types, the effect is still observable on hardwoods. Olsson et al. (2018) report the high correlation between IP from fibre orientation scanning and bending strength for oak (R^2 value of 0.56) and Rais et al. (2021) for a relationship between the slope of grain and tensile strength for beech (R^2 value of 0.638). By using the multivariate models considering dynamic MOE and fibre angle, high prediction accuracy is obtained.

To detect fibre deviation, other non-destructive methods have also been applied including microwave measurement (Denzler and Weidenhiller, 2015), electrical field strength measurement (Norton et al., 1974; McDonald and Bendtsen, 1986) and thermal conduction properties (Daval et al., 2015). Ehrhart et al. (2018) used automated visual analysis of the spindle patterns to detect the fibre flow on the surface of beech timber. Schlotzhauer et al. (2018) compared tracheid measurement, microwave measurement and electrical field strength measurement and concluded that none of the methods is suitable for all species at once. To determine the fibre deviation for a specific species, the method with acceptable accuracy should be chosen and calibrated individually and carefully.

1.4.4 Combined visual and machine strength grading

As currently no grading machine is available that can detect knots in hardwoods and estimate the MOE, the combination of visual grading and machine grading parameters is used. The system takes advantage of applying grade boundaries to two criteria – knottiness and dynamic MOE – with high correlation to strength and stiffness. So far, the approach is being used to grade beech lamella visually with additional requirements on dynamic MOE for beech glulam (Frese and Blaß, 2007). Recent work by Ehrhart et al. (2016b) on beech confirms the selected approach. A similar procedure has been applied to red maple lamellas in the US (Janowiak et al., 1997). To produce high-quality outer lamellas, Manbeck et al. (1993) and Janowiak et al. (1997) specified supplementary requirements on the dynamic MOE, on the slope of grain and on the edge knot criteria in addition to the visual grading in accordance with grading rules for north-eastern lumber (NELMA, 1991). German national approval for oak glulam by Holz Schiller (Z-9.1-821, 2013) also defines additional requirements on knottiness.

1.4.5 Quality control

By applying the thresholds, either visual or machine grading thresholds the piece of timber is assigned to a specific strength class in section 1.4.1. To ensure that graded timber pieces reveal the actual timber properties, different quality control options are available.

For the visual strength grading the assignments to the strength classes for already existing thresholds of the national grading rules are established in accordance with EN 384 within the European normative framework and are valid for a combination of wood species and countries.

For the machine strength grading two fundamental methods of the quality control are available. Those are machine control and output control. In Europe, the machine-controlled method is broadly used, whereas in North America or Australia more emphasis is put on output control. For the machine controlled method the machine settings/thresholds are determined on a large sample prior to the production process and remain constant afterwards. For the output controlled method the specimens from the daily production are sampled and used to control the grading process, particularly the settings. If quality deviations are registered the machine settings will be adjusted. This method is suitable for grading limited timber sizes, species and grades or when individual settings for a certain raw material are wanted (Bengtsson et al., 2008).

For the output control of timber, the CUSUM method proposed by Warren (1978) remains the most used one. It was implemented in EN 14081-3 (2012). The major advantage of the method, compared to the other statistical process control tools, is the ability to accumulate the information during the control procedures over time, as the deviation from the reference values are calculated and the cumulative sum tabulated. For the CUSUM method two different chart types - attribute chart and variable chart can be used. An attribute chart is used to control the 5^{th} percentile of strength and a variable chart to control the deviation of the mean MOE from the required value. The specimens are proof-loaded and the number of specimens failing the proof-load is registered and used to control the 5^{th} percentile of tensile strength. The CUSUM chart for characteristic strength values shows a low performance for the detection of quality shifts (Sandomeer et al., 2007; Ziethén et al., 2010).

Both machine and output control reveal difficulties associated with the high variability in the wood resource that can occur especially over multiple growth regions. Thus, machine control is not able to detect quality shifts as no monitoring of the output in terms of machine reading or destructive test is obligatory. Output control, as mentioned earlier, is able to react to quality deviations, however, not to the short-time quality variations.

Real-time control methods gain more and more attractivity, as more information gathered during the grading is available and can be utilized. Sandomeer et al. (2008) proposed a system by which systematic quality variations are identified during the grading.

This is done using the Bayesian regression analysis to estimate the predictive characteristics based on the non-destructive reading. If the shift is identified the settings and parameters are reassessed on the new small sample (e. g. 50 specimens). Deublein et al. (2010) have shown possibilities to detect quality shifts using non-destructive CUSUM. Further, Turk and Ranta-Maunus (2010) have introduced the method of adaptive settings. This method uses the measurements during the grading procedure to continuously adapt the machine settings. In comparison to a machine-controlled method for one growth region better properties and higher yields could be achieved.

1.5 Normative framework

1.5.1 Structural sawn wood

The overall framework for the production of solid timber is provided by the product standard EN 14081. The standard regulates requirements on solid timber and, particularly, on the grading procedures. Grading in accordance with European product standard for strength graded structural timber EN 14081-1 can be done either visually or by machine.

In the case of visual strength grading, the standard refers to national grading rules, such as DIN 4074 in Germany or INSTA 142 in Scandinavia. Using national standards, the timber is assigned to the visual grades. Visual grades alone provide no information about the mechanical property values of graded timber. The assignments can be regulated in visual grading reports, which are written in accordance with regulations of EN 384 valid at the time of report preparation or submission. EN 384 provides necessary steps, requirements on sampling of timber and calculation of characteristic properties in order to obtain an assignment to the strength class. The characteristic properties themselves are calculated using the procedures listed in EN 14358. To obtain the mechanical properties, the visual grades are translated into the strength classes of EN 338 using EN 1912. For each combination of species, growth region (origin) and visual grade, the counterpart strength class can be found.

Machine strength grading is regulated in European standard EN 14081-2, EN 14081-3 and EN 14081-4. EN 14081-2 describes the procedure and requirements for the determination of the initial machine settings in the case of the so-called machine-controlled system. EN 14081-3 describes the procedure for the factory production control in the case of the output-controlled system. The difference between the systems is covered in section 1.4.3. EN 14081-4 lists only a limited number of grading machine settings for the machine-controlled system. The most recent settings for a specific grading machine are published in Approved Grading Reports (AGRs) and corresponding tables and are used for the grading.

The mechanical property values for solid wood are listed in the strength class system. In Europe, EN 338 (2016) lists the strength classes - the material profiles - with defined characteristic property values. The standard distinguishes between C and T-Classes for softwoods and D-Classes for hardwoods. The classes C and D are defined based on the bending test and the T-Classes are based on the tension test. Historically, the C and D classes were introduced first and therefore, the abbreviation C stands for ‘Coniferous’ and D for ‘Deciduous’, without referring to the testing mode. The abbreviation T for tensile strength classes was introduced in recent decades and refers to softwoods only. The recommendations to extend the standard to hardwoods have already been presented by Hübner (2013). Values for other properties than tensile strength and MOE were determined in a project run at Wood Research Munich for example by Westermayr et al. (2017), Hunger and Van de Kuilen (2015) and Van de Kuilen et al. (2017).

To assign certain wood samples to the strength classes the major characteristic properties are used, which are: 5^{th} percentile of tensile/bending strength, the mean static MOE, and the 5^{th} percentile of the density. Depending on the product, application properties in bending or in tension are of interest. For glulam lamellas, the tensile strength profiles are the preferred ones. So far, these were regulated in EN 14081-4 with a variety of classes in tension for softwoods (T-Classes). The characteristic property values are calculated using the parametric method (for $N < 40$) and the non-parametric method ($N \geq 40$) according to EN 384 and EN 14358. For the parametric method, a certain distribution of the mechanical parameter is assumed. For the strength, as proposed in probabilistic model code JCSS (2006) usually the log-normal distribution is assumed, even though a normal distribution is often better (e.g. Van de Kuilen and Blass, 2005). In addition, for the characteristic value calculation, the confidence limit is applied.

Other properties are derived from major characteristic properties using equations given in EN 384 (2016). For tension strength classes, the bending strength is derived from the tensile strength and vice versa. Furthermore, other properties such as compression along the grain, strength properties perpendicular to the grain and shear strength are derived.

All properties are tested in accordance with EN 408, which provides test guidelines and requirements for the testing of solid wood in structural dimensions, as well for engineered wood products.

1.5.2 Glued laminated timber

In Europe, EN 14080 (2013) regulates the production of glulam and is restricted to softwoods only. For hardwood glulam national regulations, European technical approvals, or the old EN 14080 (2005), which was not restricted to softwoods, are used. Several German technical approvals exist dealing with Dark-Red-Meranti (Z-9.1-577, 2004), beech (Z-9.1-679, 2013), oak (Z-9.1-704, 2012; Z-9.1-821, 2013) and chestnut ETA-13/0646 (2013). Each approval defines the requirements on the lamellas and their mechanical property values. Under the old species-independent EN 14080 (2005), dif-

ferent types of glulam have been produced with for instance ash, iroko (*Milicia excels*), guariuba (*Clarisia racemosa*) and poplar (*Populus* ×*euramericana*, 'Neva' clone) and eucalyptus (*Eucalyptus grandis*) (Castro and Paganini, 2003).
Within the technical approval, the visual grading classes, often 'LS'-Classes in accordance with DIN 4074-5 (2008), or 'LS'-Classes extended by further requirements on the machine grading parameters such as dynamic MOE (Z-9.1-679) are used to define the requirements on lamellas. The grading requirements and the material properties are regulated within a single approval, compared to the softwoods where those procedures are separated. The approach is shown in detail by Frese and Blaß (2007).

2 Objectives

Changing environmental conditions and advancing silvicultural practices have led to a higher share of hardwoods in European forests (BMEL, 2015). However, this change is currently not supported by the demand on sawn hardwood products. The total share of sawn logs accounts for approximately 60 million m^3 per annum with only 1 million m^3 hardwood logs. To solve the discrepancy between the resource availability and the actual demand, new markets/products must be established. Those should not be limited to the most common hardwood species, such as oak and beech, but also account for possible structural changes in European forests, as less prevalent hardwood species become more attractive as a mixed forest species and/or fit more the changing environmental conditions.

Such shift requires know-how and technology at least on the same level as for the softwoods. Thus, major processing steps, such as strength grading show deficits in case of hardwoods compared to softwoods. The current thesis focuses on the grading of hardwoods for engineered wood products, as one of the major processing steps. The feasibility of the production needs to be assessed in terms of the volumetric outcome and material used. Yield is therefore assessed not only in terms of strength grading but is related to the use in the production facility. For grading class assignments, usually, the testing length is assessed, to obtain a higher correlation to the mechanical properties. For the grading in production facility - grading is done over the entire length of the board.

The grading of the medium-density hardwoods is addressed regarding the following issues:

1. Mechanical properties assignment of medium-density European hardwoods that can be achieved using different state of art grading methods (Papers I, II, III, IV);

2. Property relationships for the medium-density hardwoods. The relationship between the mechanical properties as shown previously is available for bending strength applications. For applications where tensile properties are governing the design, for instance, in glulam, the relationships are not known (Paper I);

3. Application of novel non-destructive imaging methods using crosswise ultrasound for the strength grading of hardwoods (Paper IV);

4. The quality control methods for machine strength grading of large production

data for timber from multiple growth-regions and, therefore, subject to larger variation in mechanical property values (Paper V);

5. The economic feasibility of hardwood lamella production from low-dimension and/or low-quality logs and the impact of the strength grading on the total volumetric yields with a focus on the production of lamellas for glulam. This was chosen as for medium-density hardwoods small volumes are typical and this requires the optimization of raw material use. This can be achieved by targeting high-end glulam applications instead of sawn wood applications which are restricted to limited spans and cross sections (Paper VI).

3 Materials

In total, 8840 hardwood and softwood specimens tested destructively were used for the analysis. Table 3.1 gives an overview of the used material. The used data set includes samples of temperate European hardwoods: European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), maple (*Acer spp.*) and oak (*Quercus spp.*). Norway spruce (*Picea abies*) was used as a reference material, as for softwoods large production data sets are available and current standards are studied and suited primarily for spruce and other softwoods. For spruce, only non-destructive properties were used. For each specimen, prior to the mechanical tests grading parameters were determined. However, for the specimens tested perpendicular to the grain and in shear no grading data is available, as the properties are determined on smaller size samples (cf. section 4.3).

For each part of the thesis, specific samples were selected primarily based on the quantity and entity of the measured parameters (visual and machine grading, test method).

This dissertation is based on the following six peer reviewed publications:

1. Paper I: Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech

2. Paper II: Visual and machine strength grading of European ash and maple for glulam application

3. Paper III: Strength grading of hardwoods using transversal ultrasound

4. Paper IV: Strength and stiffness predictions with focus on different acoustic measurement methods

5. Paper V: Quality control for machine strength graded timber

6. Paper VI: Analysis of economic feasibility of ash and maple lamella production for glued laminated timber

Table 3.1: Summary of the timber data used in the publications

			Paper						
Test mode	Wood species	N	I	II	III	IV	V	VI	Reference
Tension ∥	Eur. ash (*F. excelsior*)	740	×	×	×[a]	×		×	
		466	×						Van de Kuilen and Torno (2014)
	Eur. beech (*F. sylvatica*)	218	×			×			Glos and Lederer (2000)
		300	×						Blass et al. (2005)
	Maple (*A. spp.*)	381	×	×	×[b]	×		×	
	Norway spruce (*P. abies*)	4158					×		
Bending	Eur. ash (*F. excelsior*)	324	×			×			Glos and Torno (2008a)
	Eur. beech (*F. sylvatica*)	224	×			×			Glos and Lederer (2000)
	Maple (*A. spp.*)	459	×			×			Glos and Torno (2008b)
	Oak (*Q. spp.*)	336				×			Glos and Lederer (2000)
Compr. ∥	Eur. ash (*F. excelsior*)	457	×						Van de Kuilen and Torno (2014)
	Eur. beech (*F. sylvatica*)	383	×						Blass et al. (2005)
Tension ⊥	Eur. ash (*F. excelsior*)	56	×						Westermayr et al. (2017)
	Eur. beech (*F. sylvatica*)	32	×						Westermayr et al. (2017)
Compr. ⊥	Eur. ash (*F. excelsior*)	70	×						Westermayr et al. (2017)
	Eur. beech (*F. sylvatica*)	54	×						Westermayr et al. (2017)
Shear	Eur. ash (*F. excelsior*)	73	×						Hunger and Van de Kuilen (2015)
	Eur. beech (*F. sylvatica*)	85	×						Hunger and Van de Kuilen (2015)
	Oak (*Q. spp.*)	24	×						Van de Kuilen et al. (2017)
$\sum$		**8840**							
NDT	Norway spruce (*P. abies*)	279,235					×		
$\sum$ ALL		**288,075**							

[a]sub-sample of 7 ash boards selected
[b]sub-sample of 9 maple boards selected for the full scan and 63 for a scan with coarse grid

Paper I utilizes almost all tested hardwood data as it requires data tested in different testing modes to analyse the relationship between the properties. Machine grading readings were not available for all samples. Particularly, samples for the publications II and VI included visual and machine grading data and the tracking protocol from the log to the timber. This information allowed to analyse the grading of the hardwoods (Paper II) and the yield in each processing step (Paper VI). From the mentioned samples only a small sub-sample could be used for the Paper III as the laboratory device allowed to process only limited number of boards in a reasonable time. The missing grading machine readings, in high quantity, are the reason why the different machine control options are tested on softwoods (Paper V). Whereas for softwoods large data sets are available at production facility, only limited data are available for hardwoods.

4 Methods

4.1 Visual assessment of wood samples

The visual assessment was done according to DIN 4074-5 which specifies the German national grading rules for hardwoods - the common grading standard for medium-density hardwoods in Central Europe. Major grading criteria are: knots, pith and cracks in case of bending applications.

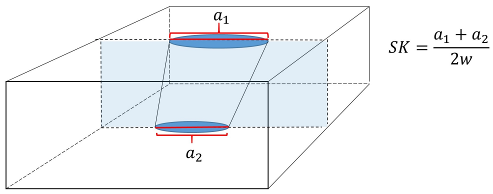
Single knot (SK) is defined as the ratio between the size of the largest knot related to the width of the board (Figure 4.1(a)). The size includes dimensions (width parallel to the edge) of an individual knot on all board surfaces;

Knot cluster (KC) is defined as the ratio between the size of the largest knot related to the width of the board (Figure 4.1(b)). The size includes dimensions (width parallel to the edge) of an individual knot on all board surfaces;

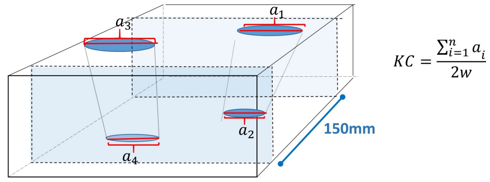
Edge knot (E) or DIN Astansammlung Brett (DAB) is a multiple knot criterion, which considers all knots appearing in a moving window of 150 mm. Therefore, the spread of all knots over the 150 mm window is related to the width of the board (Figure 4.1(c)). Both grading criteria (SK and KC) are relevant to the grading of boards and lamella. The low knottiness values indicate small knot size and/or in case of KC rare occurrence of the knots;

Fibre deviation is an important grading criterion for the visual grading of hardwoods. DIN 4074-5 specifies it as global fibre orientation, which is measured as an aberration of fibres from the central axis of the board and determined over a larger span. The parameter can be measured either by scribbling using a needle or determined on drying cracks, which occur in the fibre direction if any are available. The fibre deviation was measured during the knot registration if any obvious fibre deviation was observable. After the mechanical testing the fibre deviation was additionally measured on the failure pattern;

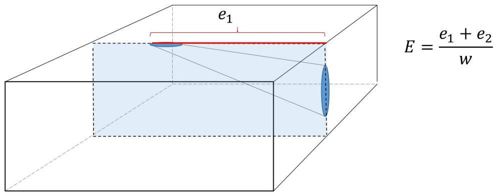
Pith is another important grading parameter. Only the presence of the pith is considered and registered. If graded according to DIN 4074-5 for hardwoods, it is a general exclusion criterion for hardwoods. The only exception is the low-quality oak beam (LS 7 quality).



(a) SK



(b) KC



(c) EK

Figure 4.1: Knottiness criteria after DIN4074-1:2008: Three simple graphs: (a) single knot (SK), (b) knot cluster (KC), (c) edge knot (EK) (Paper II)

4.2 Machine grading parameters

Dynamic MOE is an important machine grading criterion. For the longitudinal stress wave (LSW), a measurement hammer is used to generate a stress wave. The signal is recorded by means of a microphone or an accelerometer. Both measurements are performed at the laboratory of the TU Munich for consistency check, as they provide similar results. In industrial facilities a laser vibrometer can be used to record vibrations contact-free. By applying the FFT-transformation, the eigenfrequency is calculated. The E_{dyn} is calculated by combining the eigenfrequency (f) with length (l) of the specimen and density (ρ) measurement as shown in Eq. 4.1. In following, this method is denoted as longitudinal vibration (LV) method. Alternatively, ultrasound wave speed can be used, which functions according to the same principle.

$$E_{dyn,LSW} = 4 \cdot \rho \cdot l^2 \cdot f^2 \tag{4.1}$$

X-ray attenuation measurement (XRA) The X-ray attenuation allows to measure the density differences within a timber piece. Generally, the higher the density, the higher the attenuation of the X-ray between the X-ray source and the sensor. This is of advantage for wood defect detection. For softwoods, the density of the knots is twice as high as the density of clear wood, which allows to detect the knots. Figure 4.2 shows a typical measurement for ash, with clearly visible knots. It also becomes evident that the higher density is at the fibre compression at the interface between the knot and the clear wood.

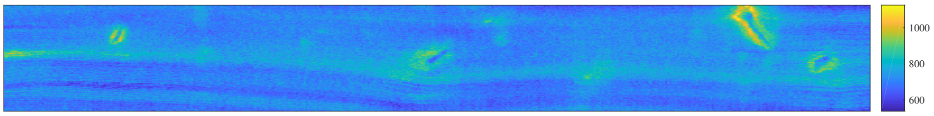


Figure 4.2: X-Ray scan of ash board using GoldenEye 706 from MiCROTEC

Transversal ultrasound scan (TUS) The hardwood specimens were scanned using a laboratory scanner developed at the TU Munich (Figure 4.3) (Yaitskova et al., 2015). The measuring unit consisting of ultrasound transducers is moved along the specimen in x and y-direction within the scan area (Figure 4.3(b)). The measuring unit used to measure and generate ultrasound signal included Pundit Lab+ with two dry-contact piezo-ceramic transducers, with a central frequency of 54 kHz from PROCEQ.

For each specimen, the area of 9 times the width was scanned by the device resulting in a total of 82,800 measuring points. For each measuring point, different parameters of ultrasound signal – Time-of-Flight (ToF), amplitude, energy, and spectral density – were calculated. For each parameter, a 2D image was generated and used to distinguish between the wood features and clear wood using image processing algorithms and optimization routines. For the current analysis, only ToF is used. The ToF was calculated using the threshold value of the signal amplitude, exceeding which the time was detected. Based on cluster analysis, the conclusion could be drawn that for a 54 kHz transducer time-of-flight provides sufficiently accurate results for defect detection. Other parameters, such as amplitude, did not provide any additional information on the defects.

As the time-of-flight is dependent on the growth ring alignment, the velocity in the radial direction is higher compared to the tangential direction (Yaitskova and Van de Kuilen, 2014). Therefore, during the processing, first, the macroscopic structure represented as a growth ring alignment (differences between radial and tangential direction) is subtracted from the image. Generally, an analytical approach to build the radial-tangential profile (RT-Profile) is possible. However, building such a profile requires additional information on the position of the graded piece towards the pith. Furthermore, as the position of the pith might change in x, y, z direction its use includes some uncertainties. Therefore, for grading purposes, a numerical approach is more suitable, leading to a creation of a filter profile applied to the image. The basic idea behind it is to skip the local inhomogeneities. By applying a median filter to the specimens, such a profile was created. The approach is in detail described in Paper III.

4.3 Destructive tests

The mechanical properties of solid wood were tested in accordance with the specifications listed in EN 408 (2010). The specimens were tested in bending, tension, compression, longitudinal and perpendicular to the grain direction. All samples prior

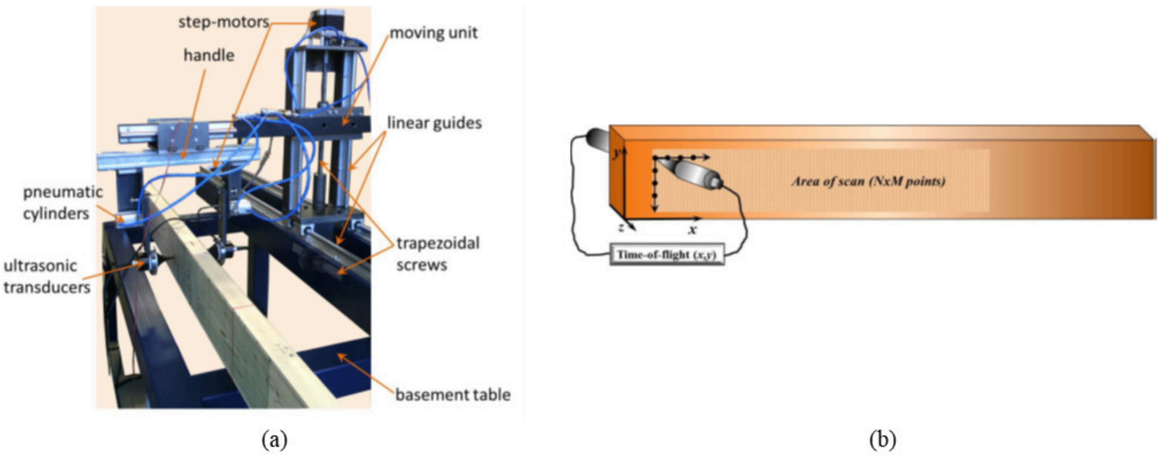


Figure 4.3: Mechanical structure of TUS (a) and the measuring geometry (b) (Yaitskova et al., 2015)

to testing were climatized under the reference conditions (20°/65 RH). The following Figure 4.4 gives an overview of the setups used to determine the mechanical properties. For the current thesis, 1121 ash and maple specimens were tested.

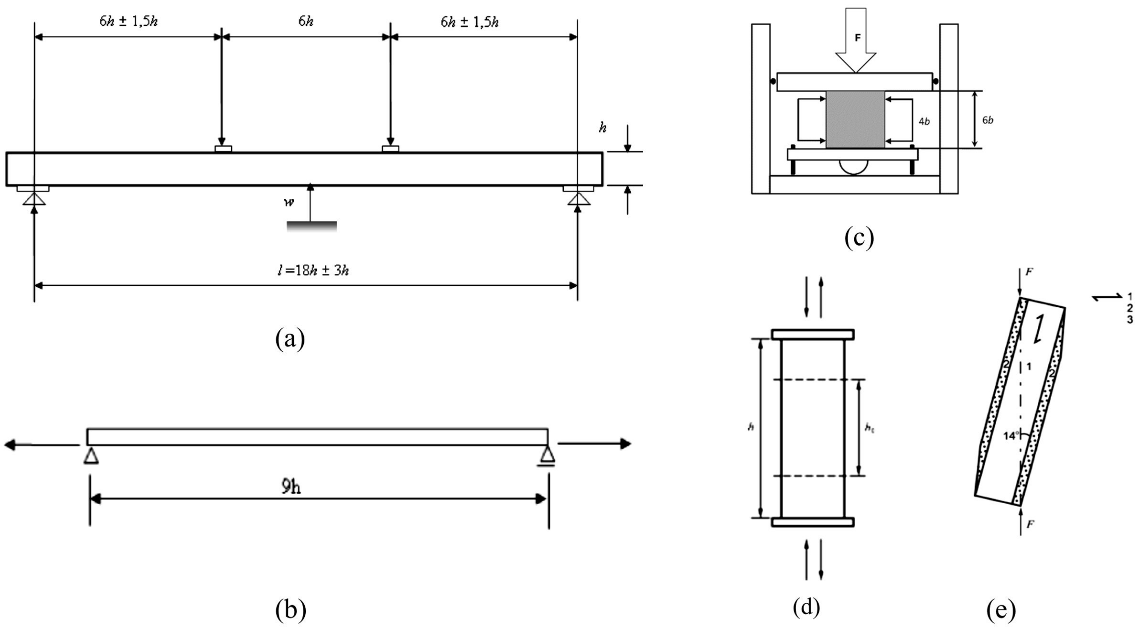


Figure 4.4: Mechanical testing of specimens according to EN 408. Test modes: (a) edgewise bending, (b) tension parallel to the grain, (c) compression in grain direction, (d) compression and tension perpendicular to the grain, (e) shear (Paper I)

4.4 Multi-objective optimization

4.4.1 General information on multi-objective optimization

Real life decisions contain several, often conflicting, objectives that prevent a simultaneous optimization. As a result, not a single solution but rather a set of optimal solutions, so called Pareto-optimal solutions, is the target of multi-objective optimization. The Pareto-optimal solution is not dominated by any other solution in the objective feature space, meaning that this solution is not worse than other solutions in all objectives and is at least better in one (Konak et al., 2006). The principle of non-dominance is illustrated in Figure 4.5. Whereas the solution B is a non-dominant solution, the solution A is dominated by B. Based on the obtained set of solutions, also called Pareto front, a designer can make a trade-off on a limited number of solutions, rather than considering the full range of possible solutions. Such solutions would allow for sawmillers to maximize yield in certain classes or optimize the strength profile, or both in a multi-objective space.

4.4.2 NSGA-II Algorithm

To find a set of potential solutions in the current study the Fast Non-Dominated Sorting Genetic Algorithm, called NSGA-II, introduced by Deb et al. (2002) was used. The NSGA-II is a widely used powerful optimization algorithm. For all genetic algorithms, the underlying principle is similar - the extinction of weak and unfit species by the natural selection (Konak et al., 2006). Based on their fitness, stronger individuals have a greater chance to pass in the next generation. In our case, an individual is a solution - a combination of yield and tensile strength class obtained by grading with certain grading boundaries. As the algorithm operates, fitter solutions survive from generation to generation (Konak et al., 2006). The NSGA-II has several key features such as elitism – meaning that the best solutions are retained during the lifetime of

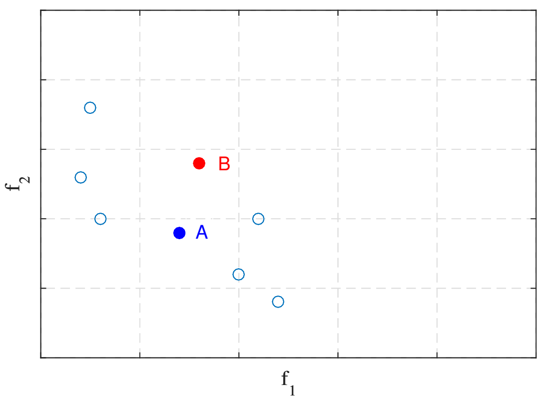


Figure 4.5: Explanation of the non-dominance principle with solution A dominated by B

the algorithm or fast non-dominant sorting algorithm (Deb et al., 2002). Basically, the algorithm runs through the following steps:

1. **Initial population**
   The initial population is created randomly out of the possible ranges for the decision variable.

2. **Non-dominant population sorting**
   The best individuals are selected for the next generation based on their fitness, whereas the lower valued are rejected and newly generated solutions take their place. Therefore, the NSGA-II uses a fast non – dominant sorting algorithm to sort individuals in several non – dominant levels/fronts. The individuals in the first front are non-dominant, whereas the individuals in the following front are dominated by the solution in the first front.

3. **Crowding distance**
   Crowding distance is used to assure the uniform spread of solutions (diversity) in the next population. The individuals from the non-dominant front that pass in the next generation are selected. The crowding distance is the distance between two neighbour solutions $z_k(x_{n+1,k})$ of the same non-dominant front along each objective. It is calculated for each objective separately using the equation (Konak et al., 2006):
   $$cd_k(x_{0,k}) = \frac{(z_k(x_{[n+1,k]}) - z_k(x_{[n-1,k]}))}{(z_k^{max} - z_k^{min})} \tag{4.2}$$

4. **New population**
   Creating a new population is an important step within the algorithm. New population R_t in generation t is a combined population of the population P_t as a part of the population P_{t-1} selected for the next generation based on non-dominance sorting (step 2) and crowding distance (step 3) and an offspring (children) population Q_t produced using the procedures selection, crossover and mutation. To create the offspring population for a new generation, at first, some individuals are selected using the crowding tournament selection operator (non-dominant rank r and the local crowding distance). Afterwards, the crossover and mutation are applied to produce the new generation. During the crossover, a new solution inherent to the characteristics is produced, whereas a mutation provides changes in the initial values of some genes by a chance and produces gene values different to those of the parents. The NSGA-II is designed for minimization problems. To maximize the objective functions using NSGA-II, the maximization problem is turned into the minimization problem by multiplying the objective function with -1 during the run-time of the algorithm.

4.4.3 Optimization procedure

The aim of the current multi-objective optimization is to find the combination of limits for the grading criteria that maximize the yield in the strength classes and their mechanical properties. On the one hand, the maximum yield in a certain strength class or strength class combination is desired, and on the other hand, the optimized strength class assignment.
For this purpose, an objective function used by the NSGA-II to find the possible solutions is defined as follows. The optimization was applied to the visual grading and the combined visual and machine strength grading and to the specific tensile strength classes of EN 338 and the ones proposed in Paper I. The classes are denoted as G1 G2, G3 in the following.
The visual grading and combined visual and machine strength grading are expressed as a function of the grading boundary combination (x_m):

$$f_{yield} = f(x_m^{G1}, x_m^{G2}, x_m^{G3}) \tag{4.3}$$

$$f_{class} = f(x_m^{G1}, x_m^{G2}, x_m^{G3}) \tag{4.4}$$

For combined grading, in addition to the visual grading parameters, such as SK and KC, the dynamic MOE is used. For each inserted boundary combination (x_m) the specimens in a sample are assigned to the visual grades and, thus, yield and the 5^{th} percentile of characteristic strength and the other characteristic properties are calculated. By matching the characteristic values listed in the tensile strength class system of EN 338 and the classes proposed in the current thesis (Table 5.1, p.28) the corresponding strength class is returned.
To model the decision-making process, the results of the visual strength grading in accordance with DIN 4074-5 are considered as a reference. To compare the optimization results with the reference, several combinations out of the entire set of optimal solutions are presented and discussed, such as grading to the highest possible strength class or solutions leading to the same strength class with optimized yields.

4.5 Data analysis

4.5.1 Relationship between the mechanical property values

The ratios between the mechanical properties can be distinguished between:

Relationship between the GDP The relationship between the GDPs (strength, stiffness and density) tested with the same testing mode are measured on the same specimens which allows calculating the direct ratio between the properties. This can be done either by means of regression analysis or in the case of the values for the batches of timber by calculating the characteristic values as an input for the ratios. In this sense, a batch of timber includes specimens graded to the same strength class of EN 338 using a specific grading method, such as visual or machine grading using an IP that includes a single parameter such as dynamic MOE or a combination of parameters.

Relationship between the GDPs and derived properties The relationship between the GDPs and derived properties includes the ratios of the properties tested using different testing modes (e.g. bending and compression, tension in parallel or perpendicular to the grain).
In the case of the static MOE, the same specimen can be tested in the different loading modes, for the strengths such a procedure is not possible. To derive such a ratio, a specific sampling design and/or application of the statistical methods is required. For example, the samples of the same origin and wood quality are split into different testing modes: bending, tension and/or compression. A variety of literature is available for softwoods such as Burger and Glos (1997) or Green and Kretschmann (1989). The population can be thereby graded into the strength classes using either visual or machine grading methods. By calculating the characteristic values, the ratios between the property values can be analysed.
For the current thesis, the ratios between the GDP and the derived properties, such as bending and tension and tension and compression, were estimated by grouping the samples based on the modelled strength from a combination of the knottiness and dynamic MOE, which show in general R^2 values in the range between 0.57 to 0.69 (Bacher, 2008). In addition, the selected data was of the same origin. Moreover, for tension and compression ratio, from each timber in a sample tension and compression test pieces were sawn.

4.5.2 Calculation of the characteristic property values

The characteristic property values of timber - mean value of MOE, 5^{th} percentile of tensile strength and/or 5^{th} percentile of bending strength, and 5^{th} percentile of density - were calculated according to EN 14358 (2016). Generally, the procedure given in the standard considers the uncertainty in the estimation of the 5^{th} percentile of the population by calculating the lower tolerance limit. The lower tolerance limit defines the value above which, with certain confidence level (α), a specified proportion of a sampled population (p) falls. In EN 14358 α is 75% and p corresponds to 5%. The 5^{th} percentile can be calculated either using non-parametric approach for $N \geq 40$ and/or parametric approach for $N < 40$. For the non-parametric calculation, the specimens are ranked, and the 5^{th} percentile with confidence limit is calculated as specified in EN 14358. The parametric calculation of EN 14358 considers log-normal distribution of the strength and normal distribution of the density. Both methods of the 5^{th} percentile calculation according to EN 14358 are linked to ISO 12122-1 standard.

The 5^{th} percentile calculation with confidence interval regards the uncertainty in the percentile estimation due to the sample size. The statistical uncertainty due to the sub-sample number is considered in k_s factor of EN 384 for visually graded timber, which is used as a multiplier during the calculation and changes depending on the number of sub-samples. For the machine-controlled strength grading the procedure of the initial settings derivation is restricted to several sub-samples per se.

4.5.3 Simulation of the grade determining properties

The performance of different quality control methods was assessed on the data of the real production facility (Paper V). The data set with 279,235 timber pieces provided by DOKA GmbH contains grading machine readings - indicating properties used for the assignment to the strength classes. To assess the quality control options on the data set, the grade determining properties (f_t and E_t) were simulated. Therefore, the values of the available indicating properties and the known relationships between the indicating properties (E_{dyn} and ρ) and the grade determining properties (f_t and E_t) were used as a basis. To carry on the simulation, it was assumed that the relationship between the properties (IP and GDP) in the production data set is equal to that of the laboratory data for a certain origin. The laboratory data (N = 4158) comprise data of specimens tested in tension in the laboratory of TU Munich or in collaboration with TU Munich. For the laboratory data both the measurement of the IP and GDP are available. The origin in this context was defined as a combination of countries, such as Central Europe, Eastern Europe and Northern Europe.

Based on the observations of the data set log-normal probability distribution was considered for tensile strength, dynamic and static MOE. Due to the high correlation ($R^2 = 92$) between the non-destructively measured density and laboratory density, the measurements from the production data set were considered as the real density values.

The simulation was carried out in two steps: 1) Generation of the GDP with desired variance-covariance matrix (cf. Turk and Ranta-Maunus, 2010); 2) To optimize the correlations, as the target variables observed log-normal distribution, the heuristic optimization was performed using the SA algorithm as presented by Charmpis and Panteli (2004).

4.5.4 Quality control

Quality control methods were applied to the production data set of 279,235 grading machine readings, with simulated mechanical properties (cf. subsection 4.5.3). The simulated GDP allowed to assess the performance of the methods by checking whether the requirements on the characteristic property values are fulfilled. To simulate the production process, the entire data set has beech split into shifts of 10,000 specimens each and the control procedures were applied to check whether, the required characteristic property values were met, and the yields are achieved. To grade the timber dynamic MOE - the most common machine strength grading method - is used as an indicating property.

The machine control was performed in accordance with EN 14081-2 (2010). To derive the settings six sub-samples from different countries with in total of 1400 specimens were sampled from the production data set.
The procedure includes the derivation of production settings using the so-called 'excluded sub-sample method'. Based on the so derived production settings all the specimens used to derive machine setting are graded. The result of this procedure is the so-called 'assigned grade'. In further step, all boards are assigned to the 'optimum grade'. This is comparable to the assignment by a non-existing perfect grading machine ($R^2 = 1$). Afterwards, the qualification accuracy is controlled using the so-called 'cost matrix', in which the assigned and the optimum grade are compared and the impact of wrongly upgraded and downgraded specimens is estimated. If the calculation results remain within acceptable, specified limits the settings can be used.

The output control was simulated in accordance with EN 14081-3 (2012). For the daily production, a sample of n specimens was virtually proof-loaded with a proof stress f_p of $0.96 \cdot f_{t,k}$ of the tested strength class. The sample size (n) of 5 and 2 $\times$5 specimens were checked for the sensitivity of the control procedure. Beside the number of specimens that failed the MOE was measured. The results were tabulated in an attribute chart for the tensile strength and a variable chart for the MOE and were used to control the production process and detect quality shifts. For the computational calculation equations underlying the process and proposed by Warren (1978) were used. More detailed description is provided in Paper V.

The output control includes several states: 'in control' and 'out of control' if the deviation is strong enough to trigger the signal. In case 'out of control' is signalized further actions to take the process 'in control' need to be taken. Those are: the confirmation test to confirm the quality shift, settings adjustment of 2% and settings adjustment of 5%. The actions were applied successively after each other.

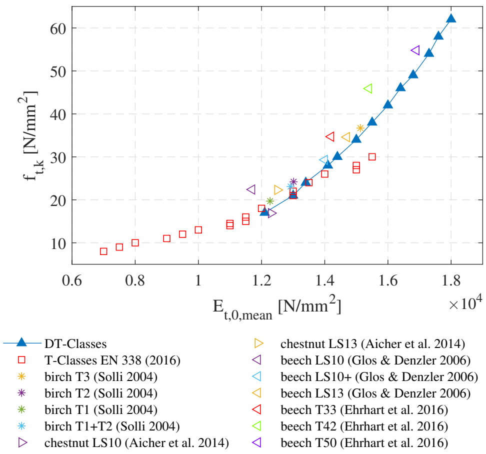
5 Results and discussion

5.1 Mechanical properties of temperate European hardwoods and their interrelationships (Paper I)

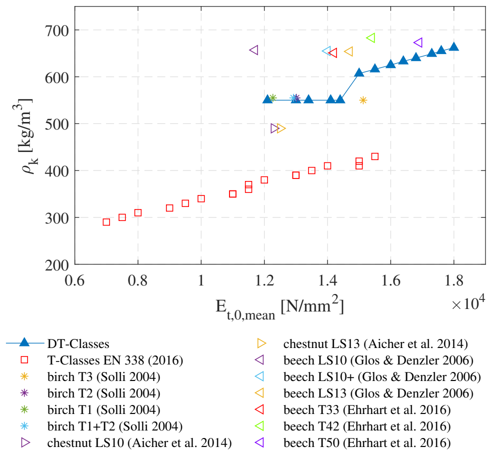
The strength class system for solid wood C-Classes is based primarily on the test results for softwood species. The equations underlying the standard are fit to softwoods and do not utilize efficiently the mechanical property values of medium-density hardwoods. Of interest are the ratios between the major mechanical and physical properties (f_t, $E_{0,mean}$, ρ_k) and between the major mechanical and physical properties and derived properties (f_m, $f_{c,0}$, $f_{t,90}$, $f_{c,90}$, f_v).
The relationship between the properties were compared on a data set of 3663 specimens, primarily ash and beech. The relationships between the major mechanical properties were optimized for tension test results. The relationship between the major properties and derived properties were adjusted.
Compared to the strength class system of softwoods, the better strength classes due to higher mechanical property values can be assigned (Table 5.1). The characteristic tensile strength values exceed the values for softwood T-Classes, which range up to 30 MPa (Figure 5.1(a)). Compared to the bending strength classes (D-Classes) more attractive ratios (e.g. bending strength to tensile strength) can be assigned to the specimens as well. Higher D-Classes were established for tropical hardwoods; thus, higher quality timber of hardwoods cannot be assigned to higher tensile and bending strength values due to the requirements on characteristic density.

Table 5.1: Proposed tensile strength classes for medium-density European hardwoods (DT-Classes) (Paper I)

	Property	DT22	DT24	DT28	DT30	DT34	DT38	DT42	DT46	DT50
Strength prop. [MPa]	$f_{m,k}$	37	40	46	49	55	61	67	73	79
	$f_{t,0,k}$	22	24	28	30	34	38	42	46	50
	$f_{t,90,k}$	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	$f_{c,0,k}$	32	33	35	36	37	39	41	42	43
	$f_{c,90,k}$	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
	$f_{v,k}$	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Stiffness prop. [GPa]	$E_{t,0,mean}$	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0
	$E_{90,mean}$	0.81	0.83	0.88	0.93	1.0	1.03	1.07	1.10	1.13
Density [kg/m^3]	ρ_k	550	550	550	550	610	610	620	630	640
	ρ_{mean}	660	660	660	660	730	730	740	750	760



(a) $E_{t,0,mean}$ vs $f_{t,k}$



(b) $E_{t,0,mean}$ vs ρ_k

Figure 5.1: Proposed tensile strength classes for medium-density European hardwoods. Relationship between the grade determining properties: (a) $E_{t,0,mean}$ vs $f_{t,k}$ and (b) $E_{t,0,mean}$ vs ρ_k in comparison to the literature values (Paper I)

The proposed classes likely do not suit all medium-density European hardwoods equally well. In particular, the density, due to variety of species with different density level makes a single value for all species less efficient (Figure 5.1(b)). A very low value might suit the majority of wood species, however, for denser species, like beech or ash, the value would be too conservative. Consequently, for European hardwoods independent specification of density would be the most efficient solution.

Within the thesis, medium-density European hardwoods were studied. For some derived properties, such as $f_{t,90}$, $f_{c,90}$ and f_v constant values were proposed. The weak correlation between density and shear strength coupled with the high variation in the property values as well as the occurring bias does not allow for specifying a reliable relationship between these variables for the assignment of shear strength values. Furthermore, the low feasibility of visual grading to distinguish between different density levels does not allow to utilize any relationships between density and shear strength. Therefore, a single constant value (7.5 MPa) based on the lowest characteristic shear strength of all samples is proposed for the strength class profiles.

Generally, observing, the entire range of wood species with higher density variation might, therefore, provide more general and more accurate prediction models and design equations. As a part of the thesis, a large data set comprising the shear strength of softwoods, medium-density European hardwoods and tropical hardwoods was analysed. Figure 5.2 shows a scatter plot for the relationship between the density and shear strength. By considering either the prediction limits for the regression equation, or the 5^{th} percentile values, as done in Figure 5.3, a conservative equation suitable for the material characteristics and design can be derived.

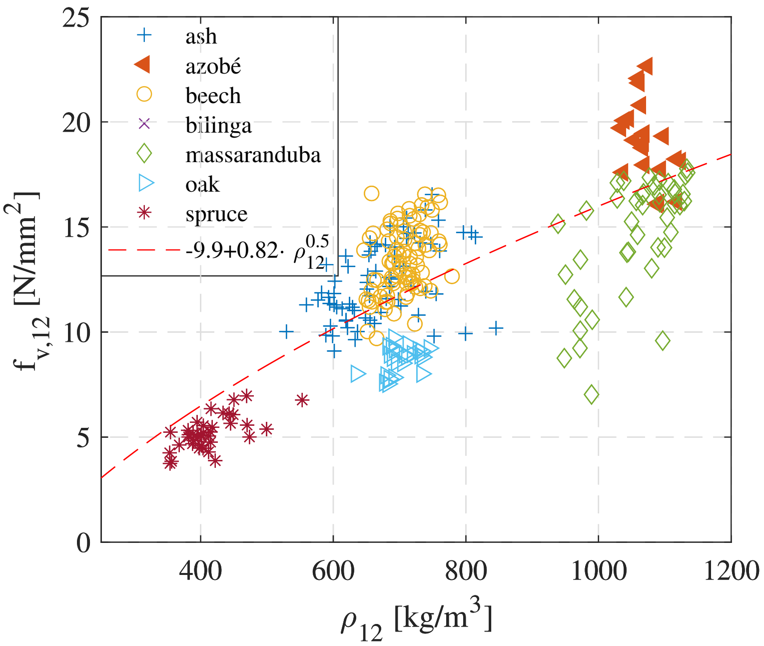


Figure 5.2: Relationship between density and shear strength for softwoods (spruce), medium-density European hardwoods (ash, beech, oak) and tropical hardwoods (azobe, billinga, massaranduba)

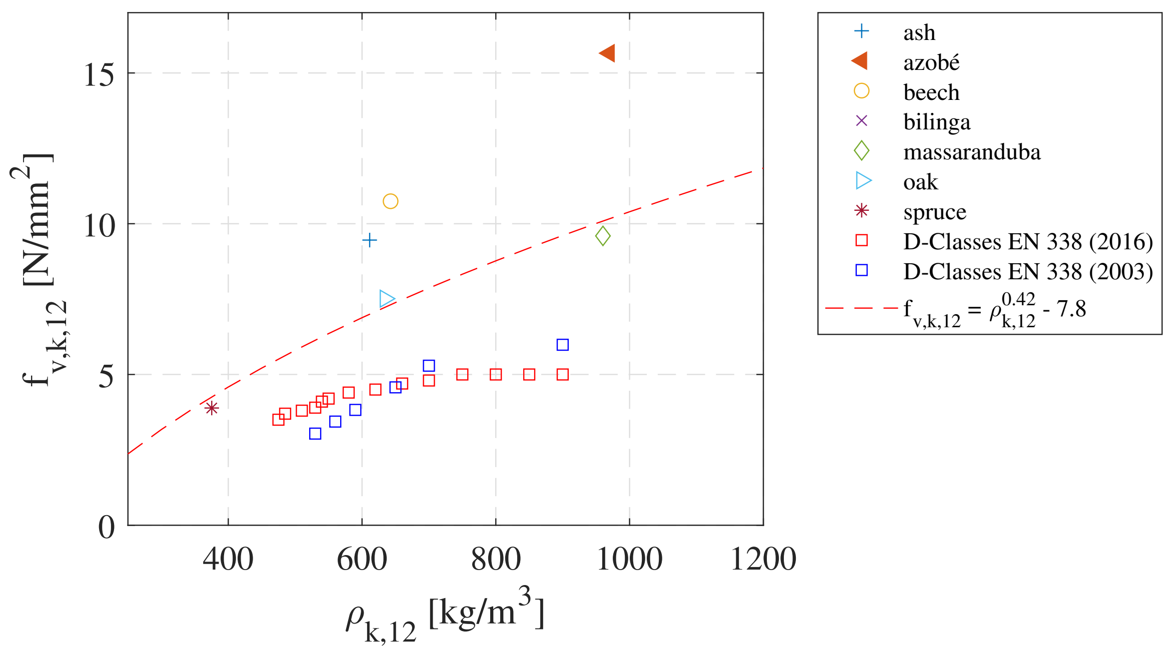


Figure 5.3: Relationship between characteristic density and characteristic shear strength for softwoods (spruce), medium-density European hardwoods (ash, beech, oak) and tropical hardwoods (azobe, billinga, massaranduba)

5.2 Strength grading of hardwoods (Paper II, III, IV)

5.2.1 Grading parameters

In the following paragraph, the visual and machine grading criteria are presented. The technologies are presented in section 5.2.2.

Throughout the papers, the performance of the different strength grading methods was analysed. In Paper II, the performance of the established methods for the softwood strength grading was determined for ash and maple. Among the grading parameters, knottiness (Single Knot and Knot Cluster) played an important role for the strength grading. Compared to the visual strength grading of softwoods, the R^2 of 0.466 for ash and 0.588 for maple (Figure 5, Paper II) can be considered as good. Such value could be achieved using non-linear fit using a second-order exponential function. This is also significant considering the different distribution of the knottiness parameters in timber. Although the knots are less frequent in hardwoods than in softwoods, the criterion is important for the strength grading, especially if automated strength grading is desired.

The importance of the knottiness for the visual strength grading in accordance with DIN 4074-5 of boards for applications in which the tensile strength is governing the design is true only for single and knot cluster criteria. The edge knot criterion, which is an additional criterion for the strength grading of boards, has less effect on strength (R^2: 0.05 – 0.098). Applying the criterion leads to a slight increase in the characteristic value of 0.6 MPa.

The national grading rules, such as DIN 4074-5 in Germany, mention several other grading parameters relevant to the strength of the timber. One of these criteria is fibre deviation. In the current study, no correlation between fibre orientation and strength could be detected. However, as shown in Paper II, even in case of the visual grading and manual detection of fibre deviation, the exclusion of boards with the visible fibre deviation considering the limits of DIN 4074 allowed to eliminate boards with lower strength values. However, in this case, only fibre deviation visible on the surface is accounted. Not all specimens showing fibre deviation can be correctly identified, as fibre deviation is very difficult to identify visually. As mentioned by Frühwald and Schickhofer (2005) for the fibre angle measurements different values between the measurement on the surface and on the failure pattern after a destructive test can be frequently observed on the same spot within a board.
The importance of fibre angle has been shown using scanner technology. As shown by Rais et al. (2021), for beech a high correlation between SOG and tensile strength with R^2 value of 0.466 as a single parameter can be achieved. The correlation, in the case of Rais et al. (2021) is of the same magnitude as for the knottiness and strength.

Another visual grading criterion having a major impact on the grading is the presence of pith. This criterion can be considered as a strict rejection criterion for hardwoods, leading to significant losses in yield, as shown in paper VI. Regarding the tensile properties, the juvenile wood shows generally lower mean strength (Paper II). However, in the case of visual strength grading to the tensile strength classes, allowing the pith and adjusting the grading thresholds lead to higher yields by maintaining the same characteristic properties.

Dynamic MOE is an important machine-grading criterion for the strength grading of timber. The performance of the parameter was analysed for a variety of soft- and hardwoods. For medium-density European hardwoods, the performance is mixed. Regarding the strength, only limited prediction accuracy (R^2 between 0.142 - 0.4) can be achieved (Paper IV). However, the dynamic MOE is the best stiffness predictor (R^2 between 0.57 - 0.792). The criterion is indispensable for assigning timber to the higher strength classes, as visual strength grading shows only a limited correlation to the stiffness (R^2 values between 0.11 - 0.23, Paper II), which is one of the major properties of timber.

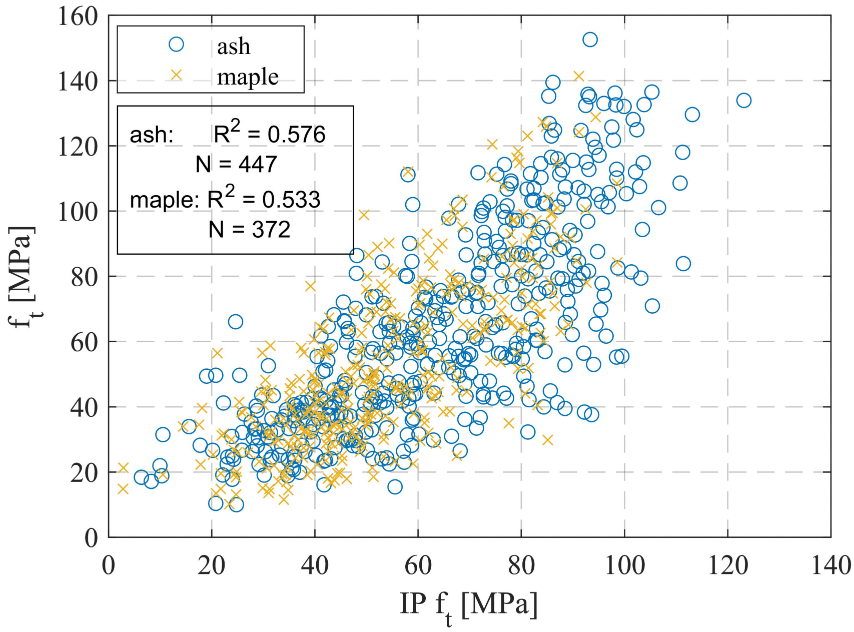
Density as a single criterion across the majority of hardwoods has no correlation to the strength properties.

5.2.2 Non-destructive methods

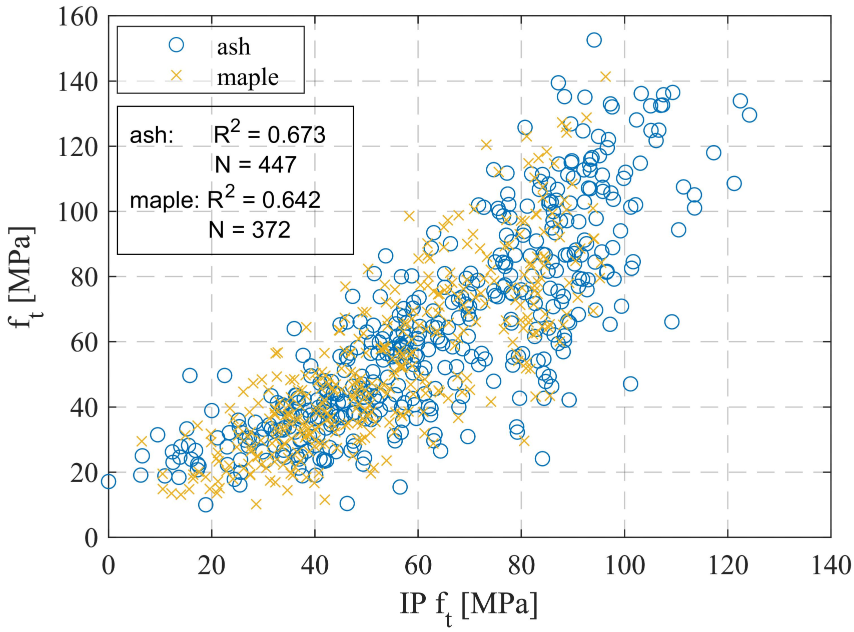
Several non-destructive techniques were used to predict the mechanical properties of medium-density European hardwoods: longitudinal vibration (LV) measurement, longitudinal ultrasound, X-ray attenuation measurement and transverse ultrasound scan.

The common practice in sawmills is the application of the LV method to predict strength and stiffness. The dynamic MOE determined using the LV method leads to limited prediction accuracy for the tensile strength. However, it shows higher correlation compared to the ultrasound measurement (Paper IV). The prediction accuracy can be increased by applying the mean value of species or sample density for the calculation of the individual dynamic MOE value. In this case, the negative correlation between density and strength, which introduces some bias to the parameter calculation, is eliminated. Generally, such behaviour is strongly related to biological and wood anatomical characteristics. The wood of the central part of the log shows higher density in hardwoods, for example, due to the extractives it includes. The juvenile wood has lower strength if compared to the mature wood. Therefore, a higher density of core wood can compensate to some extent, or amplify the frequency, without any correlation to the strength.

In Paper II, the X-ray attenuation measurement (XRA) was used to detect the knots in ash and maple. Some of the investigated specimens were additionally analysed using transverse ultrasound (TUS). The results indicate that XRA allows detecting knots; however, the detection algorithms are not optimized for hardwoods. In this case, R^2 values of as high as 0.143 for maple and 0.197 for the ash can be reached. By combining dynamic MOE and the machine knottiness, higher prediction accuracy of 0.576 can be reached. The relationship is shown in (cf. Figure 5.4(a)).



(a) Tensile strength prediction using multi-scanner system



(b) Tensile strength prediction using ideal IP

Figure 5.4: Relationship between the indicating property (IP) and tensile strength for (a) multi-scanner system (Paper II) and (b) ideal grading machine able to detect all knots on the surface and the dynamic MOE for European ash and maple

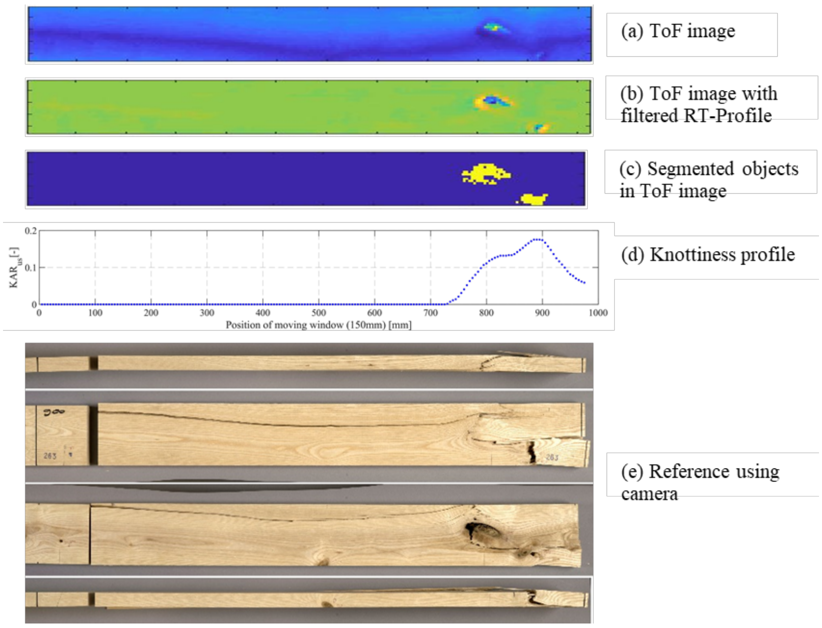


Figure 5.5: Transversal Ultrasound scan. Different processing steps: (a) raw image; (b) image with filtered macroscopic ToF profile; (c) segmented knots; (d) calculated knottiness profile in comparison to the reference (e) (Paper III)

The low correlation of dynamic MOE and machine knottiness to the strength as a single criterion justifies the research on other methods. In Paper IV, the ultrasound across grain was tested for the strength grading of hardwoods. The propagation of the ultrasound wave is dependent on the density and the elastic properties. Orthotropic differences in ultrasound wave propagation give additional information to characterize the wood samples. TUS allows knot detection (e.g. Figure 5.5). Additionally, the information on the propagation speed allows to detect the global fibre orientation. This has been done by detecting the minimum of the so-called, RT-profile, which leads to more information compared to the X-ray attenuation. Regarding the detection, one should be aware that smaller knots that penetrate less deep can be detected with less accuracy. The sample size of 16 specimens used for the analysis is small due to the time-consuming scan procedure, and in the case of industrial application, further tests are required to derive the functional relationship. TUS uses contact ultrasound, whereas for industrial applications, requiring high-speed throughput, airborne ultrasound would be preferred.

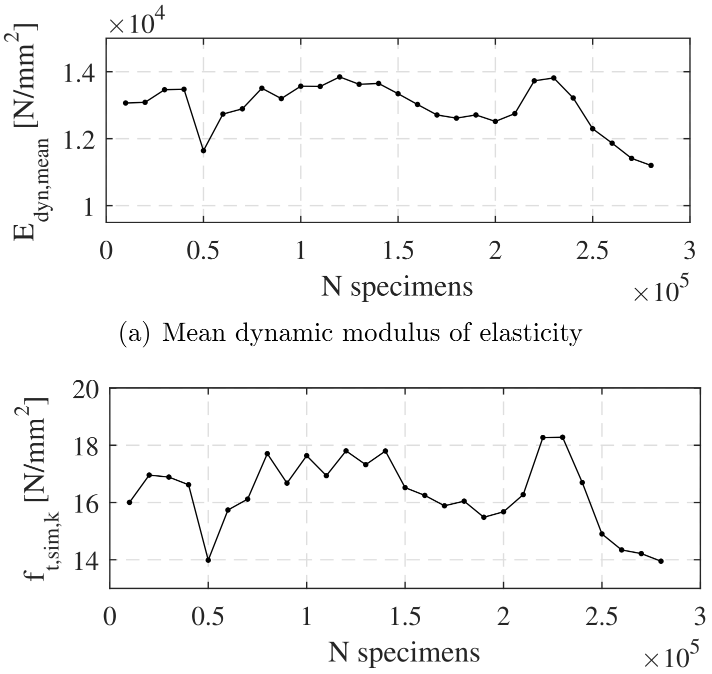
Despite the high potential, especially of combined grading models, none of the methods is able to exceed the potential of the combination of machine grading parameter dynamic MOE and of the manually measured knot criteria. Such an ideal grading model, in terms of detected local defects, allows to increase the prediction accuracy of the grading models up to 0.64 and 0.675 for maple and ash, respectively (cf. Figure 5.4(b)). This method is realised in the combined visual and machine strength grading. However, in this case, the thresholds are applied to each of the criteria separately, without calculating the prediction value using the regression model. This doesn't allow to account for interactions between the parameters.

5.2.3 Characteristic values of graded hardwoods

The visual and machine grading of the hardwoods ash and maple is not regulated for the glulam application. Whereas the assignment to the bending strength classes is possible, the tensile properties and MOE are not optimized for this kind of application. The visual grading rules in accordance with DIN 4074-5 allow classification in D40 and D30 only. Those bending strength classes indicate characteristic tensile strength of 24 MPa and 18 MPa, respectively. Furthermore, as mentioned in the section 5.1, the derived properties (f_v,$f_{t,90}$,$f_{c,90}$) are also attributed based on equations of EN 384 derived on softwoods.
The tested specimens show, generally, higher tensile strength than the ones listed currently in the standard. For the tested samples, an assignment to the higher tensile strength classes with characteristic strength values exceeding 28 MPa is possible, even if grading the timber only visually. By combining the visual and machine strength grading, higher strength classes with a characteristic tensile strength above 50 MPa and maintaining yields of 20% and more can be achieved.
The machine strength grading is represented using a multi-sensory system that combines X-ray attenuation measurement with dynamic MOE measurement. Generally, for hardwoods, the method performs less accurate, as it is based on density variations between knots and clear wood, and those differences are larger for softwoods than for hardwoods. Even though, for hardwoods, a meaningful improvement in R^2 value compared to eigenfrequency measurement and assigned characteristic tensile strength could be achieved.
Eigenfrequency, as a single method is problematic, as it has difficulties to identify fibre deviations, influences that govern the failure load (Ravenshorst et al., 2004).

5.3 Quality control options for machine strength graded timber (Paper V)

The strength grading of timber presumes that the timber assigned to the strength classes fulfils the minimum required values for the grade determining properties. To ensure the minimum required values are met, different methods of quality control can be applied. In Europe, the machine-controlled method is the most commonly used method. For the machine-controlled system, the settings are derived prior to the grading process on a large sample and remain constant during the production process. The machine 'controls' the settings. The allowable settings are documented in approved grading reports, that may contain a range of possible settings, that comprise different growth regions and cross-sections. The alternative method is the output-controlled system, which allows more flexibility, as the machine settings can be adjusted during the production, not only to gain higher values for the GDP, but also in favour of producer to increase the yields. That is possible, as the mechanical tests are performed in order to check whether the requirements on the mechanical property values are being



(a) Mean dynamic modulus of elasticity

(b) Simulated characteristic strength

Figure 5.6: Series of ungraded timber properties (a) dynamic modulus of elasticity and (b) characteristic simulated strength of specimens grouped in daily shifts of 10,000 specimens (Paper V)

met. This procedure requires, however, efforts from the producer to sample the test specimens and test them within the production control.

In Paper V, tests of the quality control procedures were applied to a large production data set of Norway spruce comprising 279,235 grading machine readings with simulated mechanical properties, tensile strength and tensile MOE based on the available grading machine reading. The data set includes multiple growth regions, defined as a combination of countries, with different mechanical property values and varying interrelationships between the properties IPs and GDP. As shown in Figure 5.6, the quality of timber is subject to fluctuations. General variation of the mechanical properties is multi-faceted and comprises an interaction of wood anatomy, environmental conditions, silvicultural treatments and processing, which are observable during the grading as the final quality of the products. This allows to simulate the robustness of the quality control to occurring quality shifts, as a result of changes in wood quality due to, for example, wood supply.

The paper examined the general possibility of both methods to cover such changes. The machine-controlled system is dependent on the initial data set for the determination of the settings. If timber during the grading shows the same proportion of timber sources as the timber for the machine settings determination, the requirements on the characteristic property values are likely to be met. However, if during the grading variations in timber quality occur, the requirements on the quality control should be set in a way that quality fluctuations are accounted for. On the other hand, if the settings are conservative, the requirement on the mechanical properties are met, but at the cost of lower yields. It has less efficiency.

Output control, as implemented in EN 14081-3 (2012), offers the ability to react to a quality shift. In case of multiple growth regions with changing quality, too low quality, or initially too low settings, in this case, 5% lower settings selected in Paper V for the control purposes can be detected. The sensitivity to detect quality shifts during the production process is, however, low. Due to the coarse design, in particular - the application of the attribute chart, the reliability of the quality is limited. Thus, smaller shifts ($< 5\%$) may remain undetected both over time and in magnitude.

Although the output-controlled system has been checked on softwoods, the general conclusions of the CUSUM approach are also valid for hardwoods. The attribute chart depends on the proportion of the specimens failing the proof-load and doesn't depend on the cov as the variable chart for MOE does.

The changing relationships between the IP and GDP are decisive for the performance of the machine control and output control in an environment with changing quality. Also, for hardwoods, such ratios are likely to change dependent on the wood quality (Paper IV). Complex models, as shown by Rais et al. (2022) are likely to minimize the occurring differences in achieved characteristic property values, due to the generally high R^2 value of. As shown in Paper IV, under these circumstances - changing wood quality, and low sensitivity to quality changes - in order to guarantee the mechanical property values conservative settings, need to be selected.

The major drawback of the output-controlled system, as of EN 14081-3 (2012) and EN 14081-3 (2018) is the inefficient use of the available information. The available grading readings are not utilized in a way to substantially improve the parameter estimation by considering Bayesian inference. The likelihood of the specimens to fail is not being considered regarding the prior information, available from the machine reading. Better approaches, such as the one proposed by Sandomeer et al. (2008) based on Bayesian regression analysis need to be considered in future.

5.4 Economic feasibility of hardwood lamella production (Paper VI)

For the production of boards for glulam applications, timber strength grading is a crucial step and leads to a product with high mechanical property values and lower variability, as shown in Paper II. To access markets with a superior product the economic feasibility is important. As no market for such products exists, the feasibility was assessed in terms of volumetric losses during the production steps. Furthermore, the sawn logs are of low quality and of low dimension, which makes the production attractive as less valued raw material is being utilized.

In total 16.25 m^3 of maple (81 log sections) and 14.89 m^3 of ash (79 log sections) were harvested from natural forest stands (mixed beech forests) in central Germany and processed to dry-plained lamella using state-of-the-art technologies. The final volumetric yields after grading amount to 9 to 18 % dependent on the grading procedure applied. Those yields are considerably lower than the ones obtained for softwood glulam lamellas.

The grading procedure had one of the major roles. By applying different grading methods yields can vary between 12.7 % for maple and 9.1 % for ash if graded visually according to DIN 4074-5 (2008) and up to 17.0 % (ash) and 17.8 % (maple) if optimized grading rules (Paper II) are applied. If combined visual and machine strength grading is applied. Higher tensile strength, if compared to 30 MPa possible for softwoods, in combination with higher derived values (Paper I) can potentially, at least partly, compensate the low yields.

Within the paper, the entire processing chain was assessed, and optimization potentials were analysed. The largest losses occur during the 'presorting and planing' step (maple: 56 %; ash: 60 %). The high percentage of the boards had to be sorted out due to bowing. By trimming these boards to shorter lengths, the waste of this production step could be reduced considerably. In addition, the sawing of the boards produced in both cases around 50 % of waste. Nonetheless, with an adjusted sawing technology, this waste can be reduced – for example through shorter log sections and optimized machine combinations. It also is advisable to define a minimum input log diameter, since the lower the log diameter is, the lower the volume yield of milling becomes. It should also be noted that some losses if compared to softwoods are not losses strictly speaking. Higher density of hardwoods leads to a higher shrinkage during the drying process, which cannot be considered as a loss, although numerically it counts as a loss.

6 Conclusions

The thesis shows the potential of using medium-density Central European hardwoods for glued laminated products. The use of hardwoods for lamella requires several processing steps to be adjusted for resource efficient and economic usage.

- Previously assumed relationships based on softwood studies are not applicable to hardwoods, neither can the existing tensile strength classes (T-Classes) can be extended by the new classes. The newly proposed DT-Classes utilize the ratios in an efficient way and allow for fitted ratios for the medium-density European hardwoods;

- As the scatter in material quality is high, only advanced grading techniques can utilize the high potential of hardwoods. Only applying the visual grading does not allow for sophisticated characteristic property values exceeding the limits of current classes (T30). By combining visual and machine grading criteria, these limitations can be exceeded. For combination of visually determined knottiness and the dynamic MOE, the characteristic tensile strength values of 42 MPa for maple and over 50 MPa for ash by maintaining feasible yields of approximately 20% and more can be achieved. For machine grading, only complex grading models, combining multiple criteria, allow an improved performance. However, in this case, the yields remain below the yields that can be achieved when visual and machine strength grading are combined;

- A possible alternative for the X-ray attenuation measurement provides the transverse ultrasound scan. By analysing the Time-of-flight and the amplitude of the signal, the knots and additionally the global slope of grain or fibre deviation can be detected. Such an improvement could activate the full potential of the machine strength grading. An grading model, with knots, detected using ultrasound or manually in combination with dynamic MOE has the potential of reaching R^2 value of as high as 0.68. However, in the case of the transverse ultrasound scan, efforts to increase the industrial applicability of the method are required;

- Optimizing the grading rules allows to increase the yield by maintaining the characteristic property values. Particularly, for the visually graded timber using the German visual grading standard DIN 4074-5, the presence of the pith, as an indicator for juvenile wood and thus for the lower quality of timber, can be excluded from the list of criteria;

- The quality control plays an important role to guarantee the required properties of timber. The output-controlled procedure, as implemented in EN 14081-3 (2012), generally allows to react to the quality variations that occur, particularly to the individual material supply of the producer, which can vary under the conditions of changing material supply. The ability of the system to react to the quality fluctuations is, however, low.

- The final performance of the wood processing from round wood to lamella is for the examined hardwoods (ash and maple) low. The final yield in terms of strength graded lumber is as high as approx. 15%, dependent on the grading rules applied, which is low compared to the softwoods. Beside an optimized processing, the strength grading plays an important role. Optimizing the grading rules and/or applying the complex models allows for provision of higher value to the produced timber, which is very sufficient considering the low yields.

7 Summary of papers

Paper I: Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech

The usage of hardwoods for engineered wood products, such as glulam, requires defined mechanical properties reflecting the actual tensile strength of the material. Currently, the European strength class system EN 338 only covers profiles for hardwoods tested in bending. In this study, the material properties of medium-density hardwoods are analysed with the focus on a total of 3663 European ash (*Fraxinus excelsior*) and European beech (*Fagus sylvatica*) specimens tested in different loading modes (tension, compression, bending, and shear). The relationships between the material properties–tensile strength, stiffness, and density–are analysed on grouped data of both graded and ungraded specimens. As a result, a tailored ratio of tensile strength to tensile MOE and density is given, which allows to utilize a higher tensile strength of hardwoods ($f_{t,0,k}$ over 30 MPa), compared to softwoods. Furthermore, the relationship of the test values and the derived values is checked. The equations for deriving the compression and bending strength from tensile strength are verified based on available data. For tensile and compression strength perpendicular to the grain and for shear strength of both beech and ash, higher strength values than the ones listed in EN 338 are possible. The relationship between the mechanical properties are combined to tensile strength profiles for hardwoods.

Paper II: Visual and machine strength grading of European ash and maple for glulam application

Medium-density hardwoods (HWs) show higher tensile strength (TS) values than softwoods (SWs). These advantages cannot be utilised effectively because HW grading is not well developed. The aim of the present paper was to analyse the utilisation potential of European ash (*Fraxinus spp.*) and maple (*Acer spp.*) grown in Central Europe, which were graded by different methods. The visual grading characteristics of 869 HW boards were determined and the dynamic modulus of elasticity (MOE_{dyn}) and X-ray attenuation (XRA) were measured by an industrial scanner. The specimens were subsequently tested in tension according to EN 408 (2010) and according to German visual grading rules show strength values of 28 MPa and 30 MPa, respectively. Machine strength grading and for a combination of manually assessed boards and MOE_{dyn} give rise to higher strength data. MOE_{dyn}, in particular, results in lamella data with 62 MPa for ash and 42 MPa for maple. There is good agreement with recently presented HW tensile profiles. Machine grading with a multisensor system allows better strength prediction compared to the MOE_{dyn} or visual strength grading. Best performance is achieved by a combined grading approach.

Paper III: Strength grading of hardwoods using transversal ultrasound

Detection of local wood inhomogeneities is important for accurate strength and stiffness prediction. In hardwood specimens, visual characteristics (e.g. knots or fibre deviation) are difficult to detect, either with a visual surface inspection or by the machine. Transversal ultrasound scan (TUS) is a non-destructive evaluation method with high potential for hardwoods. The method relies on differences in ultrasound wave propagation in perpendicular to the grain direction. The aim of this study is to estimate and analyse the capabilities of TUS for defect detection in hardwoods and prediction of mechanical property values. In the current paper, the TUS was applied to the hardwood species European ash (*Fraxinus excelsior*) and European maple (*Acer sp.*). In total, 17 boards of both specimens were completely scanned perpendicular to the grain using a laboratory scanner with dry-coupled transducers. The measurements were processed to 2D scan images of the boards, and image processing routines were applied to further feature extraction, defect detection and grading criteria calculation. In addition, as a reference for each board, all relevant visual characteristics and mechanical properties from the tensile test were measured. Using the TUS global fibre orientation, the size and the position of the knots can be detected. Those parameters correlate to the strength properties similarly or even better compared to the manual knottiness measurement and fibre angle measurement on the failure pattern. The ultrasound MOE perpendicular to the grain does not show any meaningful correlation to the elastic-properties parallel to the grain. In overall, TUS shows high potential for the strength grading of hardwoods.

Paper IV: Strength and stiffness predictions with focus on different acoustic measurement methods

Strength grading is an important step for the production of homogeneous and high-quality solid wood material. In particular, for hardwoods, the use of non-visible characteristics is indispensable. Dynamic MOE (E_{dyn}) is an important parameter widely used for grading of softwoods and applicable to hardwoods as well. There are two common ways to measure E_{dyn} - ultrasound (US) wave propagation and longitudinal vibration (LV) method. Both methods are used in practice, however, due to the different inherent measurement techniques, the results differ. The current paper analyses the stiffness and strength coefficients of determination for several temperate European hardwood species and emphasizes the differences between the two measurement systems. The performance was analysed with regard to grading techniques, testing modes for the mechanical properties (tension and bending) and wood qualities. For more than 2861 pieces of European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), European oak (*Quercus spp.*) and maple (*Acer spp.*), the E_{dyn} was measured using both techniques, and destructive tests (tension and edgewise bending) were applied. The results show that LV has higher coefficient of determination compared to the US E_{dyn}. The coefficient of determination for both methods and tensile application can be increased by calculating E_{dyn} with average density. Furthermore, the results support species-independent strength grading of hardwoods. Further research on the effect of different wood qualities and sawing patterns is required.

Paper V: Quality control for machine strength graded timber

The quality assurance of timber properties is important for the safety of timber structures. In the current study, the quality control options of timber are analysed for changing material quality under the prism of the different growth regions. Therefore, the control options–machine and output control in accordance with EN 14081–are simulated, and the performance is assessed and compared using 279,235 timber pieces from a production facility. For the data with only grading information available, the real properties were simulated based on 4158 specimens, for which destructive test results are also available. The results indicate that timber with desired material property values can be produced by both machine and output control. In direct comparison to machine control, the output control delivers timber which matches the requirements more frequently as quality shifts can be detected. Whenever lower timber quality is identified, the settings are increased. The output control system for multiple growth regions is not sensitive enough when the current attribute chart given in EN 14081-3 is used. With higher sampling rate the sensitivity can be increased. With the tested option–yield optimization-no additional yield improvement compared to machine control could be achieved.

Paper VI: Analysis of Economic Feasibility of Ash and Maple Lamella Production for Glued Laminated Timber

Background and Objectives: In the near future, in Europe a raised availability of hardwoods is expected. One possible sales market is the building sector, where medium-density European hardwoods could be used as load bearing elements. For the hardwood species beech, oak, and sweet chestnut technical building approvals already allow the production of hardwood glulam. For the species maple and ash this is not possible yet. This paper aims to evaluate the economic feasibility of glulam production from low dimension ash and maple timber from thinning. Therefore, round wood qualities and the resulting lumber qualities are assessed and final as well as intermediate yields are calculated. Materials and Methods: 81 maple logs and 79 ash logs cut from trees from thinning operations in mixed (beech) forest stands were visually graded, cant sawn, and turned into strength-graded glulam lamellas. The volume yield of each production step was calculated. Results: The highest volume yield losses occur during milling of round wood (around 50%) and presorting and planning the dried lumber (56-60%). Strength grading is another key process in the production process. When grading according to DIN 4074-5 (2008), another 40-50% volume loss is reported, while combined visual and machine grading only produces 7-15% rejects. Conclusions: Yield raise potentials were identified especially in the production steps milling, presorting and planning and strength grading.

List of all Publications

A. Khaloian Sarnaghi, A. Rais, A. Kovryga, W.F. Gard, and J. W. G. Van de Kuilen. Yield optimization and surface image-based strength prediction of beech. *European Journal of Wood and Wood Products*, 78(5):995–1006, 2020. doi: 10.1007/s00107-020-01571-4.

A. Kovryga, P. Stapel, and J. W. G. Van de Kuilen. Optimizing characteristic properties of visually graded soft- and hardwoods lamellas for the glulam production. In *Proc. of WCTE 2016*, Vienna, Austria, 2016a.

A. Kovryga, P. Stapel, and J. W. G. Van de Kuilen. Tensile strength classes for hardwoods. Paper 49-10-1. In *Proc. of 49th INTER & CIB Meeting*, Graz, Austria, 2016b.

A. Kovryga, P. Stapel, and J. W. G. Van de Kuilen. Quality control for machine strength graded timber. *European Journal of Wood and Wood Products*, 75(2):233–247, 2017. doi: 10.1007/s00107-016-1105-3.

A. Kovryga, P. Schlotzhauer, P. Stapel, H. Militz, and J. W. G. Van de Kuilen. Visual and machine strength grading of European ash and maple for glulam application. *Holzforschung*, 73(8):773–787, 2019a. doi: 10.1515/hf-2018-0142.

A. Kovryga, P. Stapel, and J. W. G. Van de Kuilen. Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech. *Wood Material Science & Engineering*, 88(6):1–14, 2019b. doi: 10.1080/17480272.2019.1596158.

A. Kovryga, J. O. Chuquin Gamarra, and J. W. G. Van de Kuilen. Strength and stiffness predictions with focus on different acoustic measurement methods. *European Journal of Wood and Wood Products*, 78(5):941–949, 2020a. doi: 10.1007/s00107-020-01584-z.

A. Kovryga, A. Khaloian Sarnaghi, and J. W. G. Van de Kuilen. Strength grading of hardwoods using transversal ultrasound. *European Journal of Wood and Wood Products*, 78(5):951–960, 2020b. doi: 10.1007/s00107-020-01573-2.

A. Rais, M. Bacher, A. Khaloian-Sarnaghi, M. Zeilhofer, Andriy Kovryga, F. Fontanini, T. Hilmers, M. Westermayr, M. Jacobs, Hans Pretzsch, and J. W. G. Van de Kuilen. Local 3d fibre orientation for tensile strength prediction of european beech timber. *Construction and Building Materials*, 279:122527, 2021. doi: 10.1016/j.conbuildmat.2021.122527.

A. Rais, A. Kovryga, M. Bacher, H. Pretzsch, and J. W. G. Van de Kuilen. Timber strength variation due to establishment density—can grading cope with it? *Forestry: An International Journal of Forest Research*, 2022a. doi: 10.1093/forestry/cpac016.

A. Rais, A. Kovryga, H. Pretzsch, and J. W. G. Van de Kuilen. Timber tensile strength in mixed stands of European beech. *Wood Science and Technology*, 56:1239–1259, 2022b. doi: https://doi.org/10.1007/s00226-022-01398-7.

P. Schlotzhauer, A. Kovryga, L. Emmerich, S. Bollmus, J. W. G. Van de Kuilen, and H. Militz. Analysis of economic feasibility of ash and maple lamella production for glued laminated timber. *Forests*, 10(7):529, 2019. doi: 10.3390/f10070529.

P. Stapel, A. Kovryga, and J. W. G. Van de Kuilen. Assignment of timber to bending and tension strength classes - Effects of calculation procedures. Paper 50-05-01. In *Proc.of 50th INTER & CIB Meeting*, Kyoto, Japan, 2017.

J. W. G. Van de Kuilen, W. Gard, G. J. P. Ravenshorst, V. Antonelli, and A. Kovryga. Shear strength values for soft- and hardwoods. Paper 50-6-1. In *Proc.of 50th INTER & CIB Meeting*, Kyoto, Japan, 2017.

M. Westermayr, M. Zeilhofer, A. Rais, A. Kovryga, and J. W. G. Van de Kuilen. Tensile strength grading of beech (Fagus sylvatica L.) lamellas from multiple origins, cross sections and qualities. *Holzforschung*, 76(5):397–407, 2022. doi: 10.1515/hf-2021-0029.

References

Aicher, S., Christian, Z. and Dill-Langer, G. (2014). Hardwood glulams – emerging timber products of superior mechanical properties, *Proc. of WCTE 2014*, Quebec City, Canada.

Bacher, M. (2008). Comparison of different machine strength grading principles, *Proc. of Conference COST E53*, New Orleans, LA.

BAFU (2015). Jahrbuch Wald und Holz 2015, *Technical report*, Bundesamt für Umwelt, Bern.

Bengtsson, C., Serrano, E., Fonselius, M. and Riipola, K. (2008). Conformity assessment for machine graded timber by using output control, *SP Report 2008:01*.

Blass, H. J., Denzler, J. K., Frese, M., Glos, P. and Linsenmann, P. (2005). *Biegefestigkeit von Brettschichtholz aus Buche*, Vol. Bd. 1 of *Karlsruher Berichte zum Ingenieurholzbau*, Univ.-Verl., Karlsruhe.

BMEL (2015). The forests in Germany - selected results of the third national forest inventory, *Technical report*, Bundesministerium für Ernährung und Landwirtschaft.

Brunetti, M., Nocetti, M. and Bacher, M. (2014). Derivation of settings for grading machine viscan for italian sweet chestnut, *Technical Report TG1/201410/03rev*, CNR-IVALSA.

Burger, N. and Glos, P. (1997). Verhältnis von Zug- zu Biegefestigkeit bei Vollholz, *Holz als Roh- und Werkstoff* **55**(6): 345–350.

Castro, G. and Paganini, F. (2003). Mixed glued laminated timber of poplar and eucalyptus grandis clones, *European Journal of Wood and Wood Products* **61**(4): 291–298.

Charmpis, D. C. and Panteli, P. L. (2004). A heuristic approach for the generation of multivariate random samples with specified marginal distributions and correlation matrix, *Computational Statistics* **19**(2): 283–300.

Chui, Y. H. and Delahunty, S. (2005). Glued engineered products made of red maple, *Technical report*, University of New Brunswick Canada.

Daval, V., Pot, G., Belkacemi, M., Meriaudeau, F. and Collet, R. (2015). Automatic measurement of wood fiber orientation and knot detection using an optical system based on heating conduction, *Optics express* **23**(26): 33529–33539.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: Nsga-ii, *IEEE transactions on evolutionary computation* **6**(2): 182–197.

Denzler, J. K. and Weidenhiller, A. (2015). Microwave scanning as an additional grading principle for sawn timber, *European Journal of Wood and Wood Products* **73**(4): 423–431.

Deublein, M., Mauritz, R. and Köhler, J. (2010). Real-time quality evaluation of structural timber, *Proc. of WCTE 2010*, Riva del Garda, Italy.

DIN 4074-5 (2008). Sortierung von Holz nach der Tragfähigkeit - Teil 5: Laubschnittholz. DIN Deutsches Institut für Normung, Berlin.

Ehrhart, T., Fink, G., Steiger, R. and Frangi, A. (2016a). Experimental investigation of tensile strength and stiffness indicators regarding European beech timber, *Proc. of WCTE 2016*, Vienna, Austria.

Ehrhart, T., Fink, G., Steiger, R. and Frangi, A. (2016b). Strength grading of European beech lamellas for the production of GLT & CLT, *Proc. of 49th INTER & CIB Meeting*, Graz, Austria.

Ehrhart, T., Steiger, R. and Frangi, A. (2018). A non-contact method for the determination of fibre direction of european beech wood (Fagus sylvatica L.), *European Journal of Wood and Wood Products* **76**(3): 925–935.

EN 14080 (2005). Timber structures. glued laminated timber and glued solid timber. requirements. CEN European Committee for standardization, Brussels.

EN 14080 (2013). Timber structures. glued laminated timber and glued solid timber. requirements. CEN European Committee for standardization, Brussels.

EN 14081-2 (2010). Timber structures – strength graded structural timber with rectangular cross section – part 2: Machine grading – additional requirements for initial type testing.

EN 14081-3 (2012). Timber structures – strength graded structural timber with rectangular cross section – part 3: Machine grading – additional requirements for factory production control.

EN 14358 (2016). Timber structures. calculation of characteristic 5–percentile and mean values for the purpose of initial type testing and factory production control. CEN European Committee for standardization, Brussels.

EN 1912 (2012). Structural timber - strength classes - assignment of visual grades and species. CEN European Committee for standardization, Brussels.

EN 338 (2016). Structural timber – strength classes. CEN European Committee for standardization, Brussels.

EN 384 (2016). Structural timber – determination of characteristic values of mechanical properties and density. CEN European Committee for standardization, Brussels.

EN 408 (2010). Timber structures – structural timber and glued laminated timber – determination of some physical and mechanical properties. CEN European Committee for standardization, Brussels.

ETA-13/0646 (2013). SIEROLAM-Glued laminated timber of chestnut. European Technical Approval, (OIB).

Forest Europe (2015). State of europe's forests 2015, *Technical report*, Ministerial Conference on the Protection of Forests in Europe.

Frese, M. and Blaß, H. J. (2007). Characteristic bending strength of beech glulam, *Materials and Structures* **40**(1): 3–13.

Frühwald, K. and Schickhofer, G. (2005). Strength grading of hardwoods, *14th International Symposium on Nondestructive testing of wood* pp. 198–210.

Fuller, J. J., Ross, R. J. and Dramm, J. R. (1994). Honeycomb and surface check detection using ultrasonic nondestructive evaluation, *Technical Report Res. Note FPL-RN-0261*, Forest Products Laboratory, Madison, WI.

Galligan, W. and Devisser, D. (2004). Machine grading procedures under the American Lumber Standard, *Proc. of WCTE 2010*, Lathi, Finland.

Giudiceandrea, F. (2005). Stress grading lumber by a combination of vibration stress waves and xray scanning, *11th International Conference on Scanning Technology and Process Optimization in the Wood Industry (ScanTech 2005)*, pp. 99–108.

Glos, P. and Lederer, B. (2000). Sortierung von Buchen- und Eichenschnittholz nach der Tragfähigkeit und Bestimmung der zugehörigen Festigkeits- und Steifigkeitskennwerte, *Technical Report 98508*, TU München, München.

Glos, P. and Torno, S. (2008a). Allocation of ash and poplar of German origin to EN 1912, *Technical Report TG1/0508/16*, TU München, München.

Glos, P. and Torno, S. (2008b). Allocation of maple of German origin to EN 1912, *Technical Report TG1/1108/26*, TU München, München.

Green, D. W. and Kretschmann, D. E. (1989). A discussion of lumber property relationships in Eurocode 5. Paper 22-6-3, *Proc. of the 22nd CIB-W18 Meeting*, Berlin, German Democratic Republic.

Green, D. W. and McDonald, K. A. (1993a). Investigation of the mechanical properties of red oak 2 by 4's, *Wood and Fiber Science* **25**(1): 35–45.

Green, D. W. and McDonald, K. A. (1993b). Mechanical properties of red maple structural lumber, *Wood and Fibre Science* **25**(4): 365–374.

Hankinson, R. L. (1921). Investigation of crushing strength of spruce at varying angles of grain, *Air Service Information Circular* **3**(259): 130.

Hausegger, G. (2017). Waldland Österreich.
URL: *http://www.proholz.at/co2klimawald/waldland-oesterreich*

Hübner, U. (2013). *Mechanische Kenngrößen von Buchen-, Eschen- und Robinienholz für lastabtragende Bauteile: Dissertation*, PhD thesis, Technische Universität Graz.

Hunger, F. and Van de Kuilen, J. W. G. (2015). Festigkeitsprofile von heimischen Laubhölzern, *Technical Report 13508/X40*, TU München, München.

Janowiak, J., Manbeck, H. B., Hernandez, R. H. and Moody, R. C. (1997). Red maple lumber resources for glue-laminated timber beams, *Forest Products Journal* **47**(4).

Janowiak, J., Manbeck, H. B., Hernandez, R. H., Moody, R. C., Blankenhorn, P. R. and Labosky, P. (1995). Effective utilization of red maple lumber in glued-laminated timber beams, *Technical Report Res. Pap. FPL-RP-541*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison,WI.

JCSS (2006). Probabilistic model code - part 3.5: Properties of timber.

Jeitler, G., Augustin, M. and Schickhofer, G. (2016). Birch | GLT&CLT: Mechanical properties of Glued Laminated Timber and Cross Laminated Timber produced with the wood species birch, *Proc. of WCTE 2016*, Vienna, Austria.

Kabir, M. F., Schmoldt, Araman, P. A., Schafer, M. E. and Lee, S.-M. (2003). Classifying defects in pallet stringers by ultrasonic scannin, *Wood and Fiber Science* **35**(3): 341–350.

Kollmann, F. F. and Côté, W. A. (1968). *Principles of Wood Science and Technology: I. Solid wood*, Springer-Verlag, Berlin.

Konak, A., David, W. C. and Alice, E. S. (2006). Multi-objective optimization using genetic algorithms: A tutorial, *Reliability Engineering & System Safety* **91**(9): 992–1007.

Manbeck, H. B., Janowiak, J. J., Blankenhorn, P. R., Labosky, P., Moody, R. C. and

Hernandez, R. (1993). Performance of red maple glulam timber beams, *Technical report*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison,WI.

Manbeck, H. B., Janowiak, J. J., Blankenhorn, P. R., Moody, R. and Hernandez, R. (1996). Efficient hardwood glued-laminated beams, *Gopu (Hg.) 1996 – Proceedings of the international wood engineering conference*, Vol. 1, pp. 283–290.

McDonald, K. A. and Bendtsen, B. A. (1986). Measuring localized slope of grain by electrical capacitance, *Forest Products Journal* **36**(10): 75–78.

NELMA (1991). Grading rules for northeastern lumber. Northeastern Lumber Manufacturers Association. Cumberland, ME.

Nocetti, M., Bacher, M., Brunetti, M., Crivellaro, A. and Van de Kuilen, J. W. G. (2010). Machine grading of italian structural timber: preliminary results on different wood species, *Proc. of WCTE 2010*, Riva del Garda, Italy.

Norton, J., Mclauchlan, T. A. and Kusec, D. J. (1974). Wood slope-of-grain indicator. U.S. Patent 3805156.

Olsson, A., Oscarsson, J., Serrano, E., Källsner, B., Johansson, M. and Enquist, B. (2013). Prediction of timber bending strength and in-member cross-sectional stiffness variation on the basis of local wood fibre orientation, *European Journal of Wood and Wood Products* **71**(3): 319–333.

Olsson, A., Pot, G., Viguier, J., Faydi, Y. and Oscarsson, J. (2018). Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce (Picea abies L.), Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and European oak (Quercus petraea (Matt.) Liebl./Quercus robur L.), *Annals of Forest Science* **75**(4).

Rais, A., Bacher, M., Khaloian-Sarnaghi, A., Zeilhofer, M., Kovryga, A., Fontanini, F., Hilmers, T., Westermayr, M., Jacobs, M., Pretzsch, H. and Van de Kuilen, J. W. G. (2021). Local 3D fibre orientation for tensile strength prediction of European beech timber, *Construction and Building Materials* **279**: 122527.

Rais, A., Kovryga, A., Pretzsch, H. and Van de Kuilen, J. (2022). Timber tensile strength in mixed stands of european beech, *Wood Science and Technology* **56**: 1239–1259.

Ravenshorst, G. J. P. (2015). *Species independent strength grading of structural timber*, Technische Universiteit Delft, Delft.

Ravenshorst, G., van der Linden, M., Vrouwenvelder, T. and Van de Kuilen, J. W. G. (2004). An economic method to determine the strenght class of wood species, *Heron* **49**(4).

Sandomeer, M. K., Köhler, J. and Faber, M. H. (2008). Probabilistic output control for structural timber: Fundamental model approach. Paper 41-5-1, *Proc. of the 41st CIB-W18 Meeting*, St. Andrews, Canada.

Sandomeer, M., Köhler, J. and Linsenmann, P. (2007). The efficient control of grading machine settings. Paper 40-5-2, *Proc. of the 40th CIB-W18 Meeting*, Bled, Slovenia.

Schafer, M. E., Ross, R. J., Brashaw, B. K. and Adams, R. D. (1999). Ultrasonic inspection and analysis techniques in green and dried lumber, *Proceedings, Eleventh International Symposium on Nondestructive Testing of Wood.*, Madison, WI, pp. 95–102.

Schlotzhauer, P., Wilhelms, F., Lux, C. and Bollmus, S. (2018). Comparison of three systems for automatic grain angle determination on european hardwood for construction use, *European Journal of Wood and Wood Products* **40**: 118.

Schmoldt, D. L., Morrone, M. and Duke, J. C. J. (1994). Ultrasonic inspection of wooden pallet parts, *Review of Progress in Quantitative Nondestructive Evaluation* **13**.

Solli, K. H. (2004). Tensile strength of nordic birch. Paper 37-6-1, *Proc. of the 37th CIB-W18 Meeting*, Edinburgh, Scotland.

Turk, G. and Ranta-Maunus, A. (2010). Approach of dynamic production settings for machine strength grading, *Proc. of WCTE 2010*, Riva del Garda, Italy.

Van de Kuilen, J. W. G. and Blass, H. J. (2005). Mechanical properties of azobé (Lophira alata), *Holz als Roh- und Werkstoff* **63**(1): 1–10.

Van de Kuilen, J. W. G., Gard, W., Ravenshorst, G. J. P., Antonelli, V. and Kovryga, A. (2017). Shear strength values for soft- and hardwoods. Paper 50-6-1, *Proc.of 50th INTER & CIB Meeting*, Kyoto, Japan.

Van de Kuilen, J. W. G. and Torno, S. (2014). Materialkennwerte von Eschenholz für den Einsatz in Brettschichtholz, *Technical Report 22017109*, TU München, München.

Warren, W. (1978). Recent developments in statistical quality-control procedures for msr, *Proc.of 4th Nondestructive Testing of Wood Symposium*, Vancouver, Canada.

Westermayr, M., Hunger, F. and Van de Kuilen, J. W. G. (2017). Strength and stiffness perpendicular to the grain of ash (Fraxinus e.) and beech (Fagus s.) in comparison to spruce (Picea a.), *Proc. of the ISCHP 2017*, Lahti,Finnland.

Westermayr, M., Stapel, P. and Van de Kuilen, J. W. G. (2018). Tensile strength and stiffness of low quality beech (Fagus sylvatica)sawn timber, *Proc. of WCTE 2018*, Seoul, Rep. of Korea.

Yaitskova, N., Nadkernychnyy, Y., Franjga, R. and Monroy, R. (2015). TUS: a breadboard for development of new wood grading algorithms using ultrasound. **URL:** *https://www.researchgate.net/profile/Natalia_Yaitskova/publication/272664728_TUS_a_breadboard_for_development_of_new_wood_grading_algorithms_using_ultrasound/links/54eaf77a0cf27a6de11559f8/TUS-a-breadboard-for-development-of-new-wood-grading-algorithms-using-ultrasound.pdf*

Yaitskova, N. and Van de Kuilen, J. W. G. (2014). Time-of-flight modeling of transversal ultrasonic scan of wood, *The Journal of the Acoustical Society of America* **135**(6): 3409–3415.

Z-9.1-577 (2004). Brettschichtholz aus dark red meranti. DIBt.

Z-9.1-679 (2013). Allgemeine bauaufsichtliche Zulassung für BS-Holz aus Buche und BS-Holz Buche-Hybridträger. DIBt.

Z-9.1-704 (2012). Allgemeine bauaufsichtliche Zulassung für VIGAM Brettschichtholz aus Eiche. DIBt.

Z-9.1-821 (2013). Allgemeine bauaufsichtliche Zulassung für Holz Schiller Eiche-Pfosten-Riegel-Brettschichtholz. DIBt.

Ziethén, R., Bengtsson, C. and Lycken, A. (2010). Machine strength grading - "output control" as a method for production control, *Proc. of WCTE 2010*, Riva del Garda, Italy.

I Paper I - Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech

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ORIGINAL ARTICLE

Mechanical properties and their interrelationships for medium-density European hardwoods, focusing on ash and beech

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ABSTRACT
The usage of hardwoods for engineered wood products, such as glulam, requires defined mechanical properties reflecting the actual tensile strength of the material. Currently, the European strength class system EN 338 only covers profiles for hardwoods tested in bending. In this study, the material properties of medium-density hardwoods are analysed with the focus on a total of 3663 European ash (*Fraxinus excelsior)* and European beech (*Fagus sylvatica*) specimens tested in different loading modes (tension, compression, bending, and shear). The relationships between the material properties—tensile strength, stiffness, and density—are analysed on grouped data of both graded and ungraded specimens. As a result, a tailored ratio of tensile strength to tensile MOE and density is given, which allows to utilize a higher tensile strength of hardwoods ($f_{t,0,k}$ over 30 N/mm^2) compared to softwoods. Furthermore, the relationship of the test values and the derived values is checked. The equations for deriving the compression and bending strength from tensile strength are verified based on available data. For tensile and compression strength perpendicular to the grain and for shear strength of both beech and ash, higher strength values than the ones listed in EN 338 are possible. The relationship between the mechanical properties are combined to tensile strength profiles for hardwoods.

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Introduction

Generally, the main properties of structural timber are listed in a strength class system. In Europe, EN 338 (2016) lists the available strength classes and their respective characteristic properties. Depending on the product application, the bending or the tension properties are of main interest. For glulam lamellas, tension classes are preferred, as the mechanical properties of glulam can be better predicted through tension classes. In addition, machine grading allows for a better prediction of tensile properties than bending properties (e.g. Ranta-Maunus 2011). So far, tension grades have been regulated in EN 14081–4 (2009). Due to the increased demand for glulam products, these grades have recently been analysed (Denzler 2012, Bacher and Krzosek 2014), and a tensile class table addressing softwoods has been introduced in EN 338 (2016). The new strength profiles are the preferred option for glulam production. The requirements for softwood glulam are regulated in EN 14080 (2013).

So far, no tension classes are available for hardwoods. For hardwood specimens, EN 338 lists only the so-called "D" classes based on the bending strength. By default, other properties, such as tensile strength, are assigned conservatively using the equations listed in EN 384. For those classes, the ratio of tensile strength to bending strength is declared conservatively with 0.6. However, as shown by Galligan *et al.* (1979), Steiger (1996), Burger and Glos (1997), and Steiger and Arnold (2009), a higher ratio is expected for higher quality timber.

New tensile classes for hardwoods would make it possible to exploit the properties of hardwoods more efficiently. Whereas the former European EN 1194 (1999) and EN 14080 (2005) standards did not distinguish between the softwood and hardwood species, the most recent version of EN 14080 (2013) is restricted to softwoods only. This means that hardwood glulam producers in Europe face additional costs in obtaining approvals for their products, as no harmonized standard is available.

The current study is aimed at analysing the relationship between the material properties of the hardwood species European beech (*Fagus sylvatica*) and European ash (*Fraxinus excelsior*). The study covers medium-density European hardwoods, which are known to have a high potential for engineered wood products and whose share in European forests is increasing with changing forestry policies towards mixed forests and higher hardwood shares. Species such as oak, beech, ash, and maple represent medium-dense hardwoods. These species are generally characterised by characteristic density values above 470 kg/m^3 and below 700 kg/m^3. Hardwoods with lower densities, such as poplar, have been assigned to softwood classes, as earlier versions of EN 338, prior to 2009, such as EN 338 (2003), did not contain hardwood classes with low densities and mechanical properties.

The present study focuses on beech and ash. Both species are known for their excellent mechanical properties. For structural applications, both species can be assigned to strength class D40, the currently highest strength class for European hardwood

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species (EN 1912 2012). The high potential of both species for engineered wood products, such as glulam, has already been reported by Frühwald *et al.* (2003) and Blass *et al.* (2005) for beech, and Van de Kuilen and Torno (2014) for ash; glulam beams with a characteristic bending strength of 48 N/mm^2 are possible for both species. Beside oak, beech is one of the most important hardwood species in Central Europe and accounting for 15% of forest area in Germany (BMEL 2015), 18.1% in Switzerland (BAFU 2015), and 9.6% in Austria (Hausegger 2017). The forest area covered by ash is lower compared to beech and oak, with, for example, 4% in Switzerland. Currently, the future of ash is threatened by fungal diseases spreading all over Europe since the 1990s and causing dieback (Pautasso *et al.* 2013). Even though the maple tested here includes only a small number of specimens, its expected mechanical properties are within the same range as that of beech and ash.

In this paper, the material properties of medium and structural-size medium-density European hardwoods, namely ash, beech, and maple, are presented with regard to their tensile strength classes. The main important characteristic values of mechanical properties are analysed, including tensile strength, tensile modulus of elasticity, density, and their relationships, followed by the relationship between tensile strength and compression and bending strength. In addition, tensile and compression strength perpendicular to the grain values are presented. The relationships analysed lead to material property profiles for medium-density European hardwoods.

Tensile strength class system

General information on strength classes

EN 338 is the European standard for the strength classes and the respective material properties. The assignment to classes is made either by means of bending or tension tests. Table 2 exemplarily shows the tensile strength classes for the softwoods that have recently been introduced.

To be assigned to a particular strength class, the values of selected characteristic properties need to be determined in accordance with EN 384, which defines the requirements for the sampling procedure and the calculation of the property values. To assign a sample to a class, the major characteristic properties, including the 5th percentile of either tensile or bending strength, the mean static modulus of elasticity, and the 5th percentile of the density, are used. If the characteristic properties match the required values for a particular class, the timber may be assigned to this class.

Other material properties are listed in EN 338 for each class, including the bending strength for the tensile classes and the tensile strength for the bending classes, compression strength parallel to the grain direction and so on. The values for these material properties are deduced based on equations given in EN 384.

Major characteristic properties of hardwoods tested in tension

The ratios between the major strength properties for the T-Classes are derived from the tensile test data for softwoods, mainly spruce and pine. The underlying relationship between the material properties has recently been analysed by Denzler (2012), and Bacher and Krzosek (2014). However, EN 338 also makes it possible to assign hardwoods with similar strength and density profiles, such as poplar or chestnut, to the tensile strength classes.

Even though assignment to the tensile strength classes is possible for hardwoods, the property relationships differ from softwoods. Firstly, for medium-density European hardwoods, higher tensile strength values than the ones listed for T-Classes are reported. Solli (2004) and Glos and Denzler (2006) reported characteristic strength values for the highest grade of the visually graded European beech and Scandinavian birch that exceed the requirements of the highest T-Class T30.

Secondly, for hardwoods, the relationship between the characteristic tensile strength ($f_{t,0,k}$) symbols and abbreviations are summarized in Table 1) and the characteristic tensile modulus of elasticity ($E_{t,0,mean}$) is different from softwood. For hardwoods with $f_{t,0,k}$) meeting the requirements of the highest T-Class T30, $E_{t,0,mean}$ values below the required 15500 N/mm^2 are reported. Particularly, the study by Glos and Denzler (2006) revealed 14700 N/mm^2 for beech, and by Solli (2004) —15130 N/mm^2 for birch. For chestnut lamellas, Aicher *et al.* (2014) determined a characteristic tensile strength of 22.3 N/mm^2 and $E_{t,0,mean}$ values of 12500 N/mm^2.

The different ratio of the characteristic strength to bending MOE for hardwoods and softwoods is stipulated in the bending strength class system of EN 338. Hardwood strength classes (D-Classes) indicate lower MOE values than softwood strength classes for the same bending strength. Green (2005) pointed to the steeper relationship between bending strength and bending MOE for North American hardwoods compared to softwoods. In contrast, Ravenshorst (2015) indicated a slightly less steep relationship but in general a rather consistent ratio of all soft- and hardwood species.

However, even within hardwoods, differences in material properties and MOR/MOE ratios are reported for species subjected to bending tests. Particularly, visually graded oak (Grade LS10+ in accordance with DIN 4074–5) from Germany tested in bending matches the requirements for MOE of strength class D30 (Glos and Denzler 2006). In contrast, for European beech and European ash specimens assigned to the strength class D30, higher values for mean bending MOE with 15900 and 14000 N/mm^2, respectively, are reported (Glos and Denzler 2006).

Relationship between values parallel to the grain

The existing strength classes for hardwoods are defined on the basis of bending tests only. For hardwoods, EN 384 (2016) gives the $f_{t,0,k}/f_{m,k}$ ratio of 0.6 with the tensile strength being estimated conservatively. The same ratio was applied to softwoods until recently (EN 384 2010). As Burger and Glos (1997) and Steiger and Arnold (2009) have shown, a higher ratio may apply to higher grades of Norway spruce (*Picea abies*). Therefore, in the recent revision of the strength class table addressing softwoods, Eq. 1 has been introduced to derive $f_{t,0,k}$ from $f_{m,k.}$ leading to $f_{t,0,k}/f_{m,k}$ ratios between 0.51

Table 1. List of symbols and abbreviations.

Symbol	Definition
b	Smaller dimension of the cross section [mm]
CV	Coefficient of variation
E	Modulus of elasticity
$E_{0,mean}$	Modulus of elasticity parallel to the grain [N/mm²]
$E_{90,mean}$	Modulus of elasticity perpendicular to the grain, mean value [N/mm²]
$E_{c,90}$	Modulus of elasticity in compression perpendicular to the grain [N/mm²]
$E_{c,90,mean}$	Modulus of elasticity in compression perpendicular to the grain, mean value [N/mm²]
E_{dyn}	Dynamic modulus of elasticity [N/mm²]
$E_{t,0,mean}$	Modulus of elasticity in tension [N/mm²]
$E_{t,0,k}$	Modulus of elasticity in tension, 5th percentile value [N/mm²]
$E_{t,90}$	Modulus of elasticity in tension perpendicular to the grain [N/mm²]
$E_{t,90,mean}$	Modulus of elasticity in tension perpendicular to the grain, mean value [N/mm²]
$f_{c,0,k}$	Compression strength parallel to the grain, 5th percentile value [N/mm²]
$f_{c,90,k}$	Compression strength perpendicular to the grain, 5th percentile value [N/mm²]
$f_{m,k}$	Bending strength, 5th percentile value [N/mm²]
$f_{t,0}$	Tensile strength parallel to the grain [N/mm²]
$f_{t,0,k}$	Tensile strength parallel to the grain, 5th percentile value [N/mm²]
$f_{t,90,k}$	Tensile strength perpendicular to the grain, 5th percentile value [N/mm²]
$f_{v,k}$	Shear strength, 5th percentile value [N/mm²]
G_{mean}	Shear modulus, mean value [N/mm²]
h	Larger dimension of the cross section [mm]
IP f_t	Modeled tensile strength [N/mm²]
KC	Knot cluster, multiple knot criterion according to DIN 4074–5 (2008) [-]
l	Length [mm]
MC	Moisture content
MOE	Modulus of elasticity
MOR	Modulus of rupture
n	Number of specimens in a subgroup
N	Sample size
ρ_k	Density, 5th percentile value [kg/m³]
ρ_{mean}	Density, mean value [kg/m³]
SK	Single knot, important grading criterion according to DIN 4074–5 (2008) [-]
w	Width [mm]

for the lowest bending strength grade C14 and 0.67 for the highest grade C30 (EN 338 2016, EN 384 2016).

$$f_{t,0,k} = -3.07 + 0.73 \cdot f_{m,k} \tag{1}$$

with $f_{t,0,\ k}$ and $f_{m,k}$ in N/mm².

For the softwood T-Classes, the tensile strength is determined by tests, while bending strength is calculated using Eq. 2. In this case, bending strength is estimated on the safe side with $f_{t,0,k}/f_{m,k}$ ranging from 0.6 for the lowest tensile grade (T8) up to 0.75 for the highest grade (T30).

$$f_{m,k} = 3.66 + 1.213 \cdot f_{t,0,k} \tag{2}$$

with $f_{t,0,\ k}$ and $f_{m,k}$ in N/mm².

In the ASTM D1990 (2000) standard, a tensile/bending strength ratio of 0.83 for the tension test values is used.

For the compression strength parallel to the grain, the following relationship is assumed in EN 384 (2016) for softwoods and hardwoods alike:

$$f_{c,0,k} = 4.3 \cdot f_{m,k}^{0.5} \tag{3}$$

with $f_{c,0,\ k}$ and $f_{m,k}$ in N/mm².

For softwood T-Classes, Eq. 3 was adopted in Eq. 4, assuming a ratio of 0.6 for $f_{t,0,k}$ / $f_{m,k}$ (Bacher and Krzosek 2014).

$$f_{c,0,k} = 5.5 \cdot f_{t,0,k}^{0.5} \tag{4}$$

with $f_{c,0,\ k}$ and $f_{m,k}$ in N/mm².

Characteristic properties perpendicular to the grain direction

EN 338 (2016) lists one characteristic tensile strength value perpendicular to the grain for all strength classes, separately for softwoods (0.4 N/mm²) and hardwoods (0.6 N/mm²). The characteristic compression strength perpendicular to the grain is given in EN 384 (2016) as a ratio of compression strength to the characteristic density, for both softwoods and hardwoods. For medium-density hardwoods ($\rho_k <$ 700 kg/m³), Eq. 5 is used, while for denser hardwoods ($\rho_k \geq$ 700 kg/m³) the higher ratio is assumed (Eq. 6).

$$f_{c,90,k} = 0.01\rho_k \tag{5}$$

$$f_{c,90,k} = 0.015 \cdot \rho_k \tag{6}$$

with $f_{c,90,\ k}$ in N/mm² and ρ_k in kg/m³.

Table 2. Tensile strength classes (T-Classes) for softwoods listed in EN 338 (2016).

	Property	T11	T14	T18	T21	T24	T28	T30
Strength properties [N/mm²]	$f_{m,k}$ [a]	17.0	20.5	25.5	29.0	33.0	37.5	40.0
	$f_{t,0,k}$	11.0	14.0	18.0	21.0	24.0	28.0	30.0
	$f_{t,90,k}$ [b]	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	$f_{c,0,k}$ [c]	18.0	21.0	23.0	25.0	27.0	29.0	30.0
	$f_{c,90,k}$ [d]	2.2	2.5	2.7	2.7	2.8	2.9	3.0
	$f_{v,k}$ [e]	3.4	4.0	4.0	4.0	4.0	4.0	4.0
Stiffness properties [N/mm²]	$E_{t,0,mean}$	9000	11000	12000	13000	13500	15000	15500
	$E_{t,0,k}$ [f]	6000	7400	8000	8700	9000	10100	10400
	$E_{t,90,mean}$ [g]	300	400	400	400	500	500	500
	G_{mean} [h]	600	700	800	800	800	900	1000
Density [kg/m³]	ρ_k	320	350	380	390	400	420	430
	ρ_{mean} [i]	380	420	460	470	480	500	520

[a] $f_{m,k} = 3.66 + 1.213 \cdot f_{t,0,k}$ in N/mm² (EN 384 2016)
[b] $f_{t,90,k} = 0.4$ N/mm² (EN 384 2016)
[c] $f_{c,0,\ k} = 5.5 \cdot f_{t,0,k}{}^{0.5}$ in N/mm² (EN 384 2016)
[d] $f_{c,90,k} = 0.007 \cdot \rho_k$ in N/mm² (EN 384 2016)
[e] $f_{t,0,k} \leq 14$ MPa: $f_{v,k} = 1.2 + 0.2 \cdot f_{t,0,k}$ in N/mm² and $f_{t,0,k} > 14$ MPa: $f_{v,k} = 4.0$ in N/mm² (EN 384 2016)
[f] $E_{t,0,k} = 0.67 \times E_{t,0,mean}$ in N/mm² (EN 384 2016)
[g] $E_{t,90,mean} = E_{t,0,mean}$ /30 in N/mm² (EN 384 2016)
[h] $G_{mean} = E_{t,0,mean}$ /16 in N/mm² (EN 384 2016)
[i] $\rho_{mean} = 1.2 \cdot \rho_k$ in kg/m³ (EN 384 2016)

The modulus of elasticity perpendicular to the grain is given as a ratio as follows:

$$E_{90,mean} = E_{0,mean}/15 \tag{7}$$

with $E_{90,mean}$ and $E_{0,mean}$ in N/mm^2.

The standard does not distinguish between $E_{t,90}$ and $E_{c,90}$. By providing a single value, the strength class system could be simplified. The test results by Hübner (2013) and Westermayr *et al.* (2017) evidence similarity between $E_{t,90}$ and $E_{c,90}$. The reported 10% difference between $E_{t,90}$ and $E_{c,90}$ is covered by the coefficient of variation (CV) with 0.27–0.36 (Westermayr *et al.* 2017).

Shear strength

For hardwood specimens tested in accordance with EN 408 (2010), the standard EN 384 (2016) defines the following relationship between bending strength and shear strength and is valid for $f_{m,k} \leq 60$ N/mm^2:

$$f_{v,k} = 3 + 0.03 \cdot f_{m,k} \tag{8}$$

with $f_{v,k}$ and $f_{m,k}$ in N/mm^2.

The constant value of 5.0 N/mm^2 is assigned for $f_{m,k} >$ 60 N/mm^2.

In contrast, EN 338 (2003) allowed higher shear strength values with increasing strength class, particularly higher shear strength for tropical hardwoods. The relationship is specified as follows:

$$f_{v,k} = 0.2 \cdot f_{m,k}^{0.8} \tag{9}$$

with $f_{v,k}$ and $f_{m,k}$ in N/mm^2.

Recently, Ravenshorst *et al.* (2016) proposed to relate shear strength to density for analysing the wood species together with density values ranging from 350 to 1150 kg/m^3, as the density indicates the total number of fibres in a species. At single species level, a low correlation has been reported. Denzler and Glos (2007) studied the shear strength for Norway spruce and found a low relationship between density and shear strength. The high variation of density and shear strength overlaid the correlation.

Materials and methods

Destructive test data

In this paper, the properties of the medium-density hardwoods European ash (*F. excelsior*), European beech (*F. sylvatica*), and maple (*Acer spp.*) are analysed with regard to tensile strength and the modulus of elasticity in tension and density. Studying the relationship between the mechanical properties of species involves a high testing effort. Data sets from different projects on hardwoods carried out at the TU München over the past years are used. Table 3 gives an overview of data available, grouped by testing type, cross-sections, and free testing length. The Central European species

Table 3. General overview of data sets, grouped by type of test and species.

Type of test	Species	Cross-sections (*bxhxl*) [mm]	Free length[a]/test span[b]	Sample size (No.)	Reference
Tension parallel to the grain	European ash (*F. excelsior*)	25×85, 30×100, 35 × 100, 50×100, 30 × 125, 35 × 125, 35×160, 50×150	765–1440 mm (9 *h*)	740	Kovryga *et al.* (2019)
		20×150, 25×110, 25×150, 30×150, 25×160, 35×110, 35×160	200 mm (1.2 *h* – 1.8 *h*)*	466	Van de Kuilen and Torno (2014)
	European beech (*F. sylvatica*)	30×120, 30×160	1080–1440 mm (9 *h*)	218	Glos and Lederer (2000)
		25×100, 35×100 25×150, 35×150	200 mm (1.2 *h* – 1.8 *h*)*	300	Blass *et al.* (2005)
	Maple (*A. spp.*)	25 × 100, 30×100, 35 × 100 25 × 125, 30×125, 35 × 125	900 (9 *h*)	381	Kovryga *et al.* (2019)
Bending	European ash (*F. excelsior*)	50×100, 50×150	1800, 2700 mm (18 *h*)	324	Glos and Torno (2008a)
Compression parallel to the grain	European ash (*F. excelsior*)	25×110, 25×110, 30×150, 25×160, 35×160	200 mm (5.7*b* – 8*b*)	457	Van de Kuilen and Torno (2014)
	European beech (*F. sylvatica*)	25×100, 35×100 25×150, 35×150	200 mm (5.7*b* – 8*b*)	383	Blass *et al.* (2005)
Tension perpendicular to the grain	European ash (*F. excelsior*)	45×180×70	180 mm (*h*)	56	Westermayr *et al.* (2017)
	European beech (F. sylvatica)	45×180×70	180 mm (*h*)	32	
Compression perpendicular to the grain	European ash (*F. excelsior*)	45×90×70	90 mm (*h*)	70	Westermayr *et al.* (2017)
	European beech (*F. sylvatica*)	45×90×70	90 mm (*h*)	54	
Shear	European ash (*F. excelsior*)	32×35×300	300 mm (*l*)	73	Hunger and Van de Kuilen (2015)
	European beech (*F. sylvatica*)	32×35×300	300 mm (*l*)	85	
	Oak (*Q. spp.*)	32×55×300	300 mm (*l*)	24	Van de Kuilen *et al.* (2017)

*below the required free length of 9*h*
[a]For tension test according to EN 408 (2010)
[b]For bending test according to EN 408 (2010)

used were sampled from the species` natural distribution areas in Germany and would be considered representative for the German growth region according to the specifications in EN 384. For beech and ash, in particular, the samples included several sub-samples from various growth areas and different sampling times. All the specimens, unless otherwise specified, were tested according to EN 408 (2010) and EN 384 (2016). Figure 1a to Figure 1e illustrate the test arrangement for the investigated properties.

For each specimen tested, density and moisture content were determined by cutting a small test piece in accordance with EN 408 (2010) and EN 13183–1 (2002) (oven dry method), respectively.

Out of 2105 hardwood specimens tested in tension, 300 beech and 466 ash specimens were tested with a free testing length of 200 mm. The beech specimens have been initially used by the Karlsruhe Institute of Technology (KIT) to develop the model for beech glulam (Blass *et al.* 2005). The ash specimens have been tested in a project of the TU München involving the mechanical properties of ash for glulam production (Van de Kuilen and Torno 2014). The intention behind using small ash specimens was to make them compatible with the Karlsruhe model for glued laminated timber simulations. For those calculations, two test pieces – one for the tension test and the other for the compression test – were cut out of a single beech lamella. Both test pieces are included in the current analysis to deduce tensile to compression strength ratio. The ratio between tensile strength, tensile stiffness, and density is solely derived on 1339 specimens tested with a free length of 9 h.

To estimate the bending strength to tensile strength ratio, samples with similar cross-sections are necessary. Therefore, out of the entire dataset, 324 ash specimens tested by Glos and Torno (2008a) in bending with a cross-section of 50 × 100 mm and 50×150 mm were selected for the determination of this ratio. Although the selected cross-section exceeds the dimensions of the lamellas typically used for glulam, the 50 mm thickness matches the dimensions of unplaned boards with a final thickness of 36 mm.

The results of shear testing, compression and tension perpendicular to the grain for medium-density hardwoods, from a project on the strength profiles of Central European hardwoods by Hunger and Van de Kuilen (2015) and Westermayr *et al.* (2017), are used to obtain the tensile profiles. Tension and compression perpendicular to the grain were tested on small-size specimens (45 × 180 × 70 for tension and 45 × 90 × 70 for compression) cut from structural timber in accordance with EN 408 (2010). For a detailed description, refer to Westermayr *et al.* (2017).

The data on medium-density European hardwoods tested within the project by Hunger and Van de Kuilen (2015), as well as data on oak (*Quercus sp.*) tested at the TU Delft (Van de Kuilen *et al.* 2017) are used to estimate the shear strength for the new tensile strength classes. The shear specimens were tested in accordance with EN 408 (2010). For the data from the TU München based on pre-tests, thicker steel plates (20 mm instead of 10 mm) were taken to compensate for the plate deformation. As demonstrated by Ravenshorst *et al.* (2016), a numerical analysis showed no difference in occurring stresses.

The moisture content (MC) during the tests differed from species to species and accounted on average for 11.0 ± 0.82% and 9.7 ± 0.69% for beech and ash, respectively. Oak specimens were tested with a higher average MC of 17.5 ±

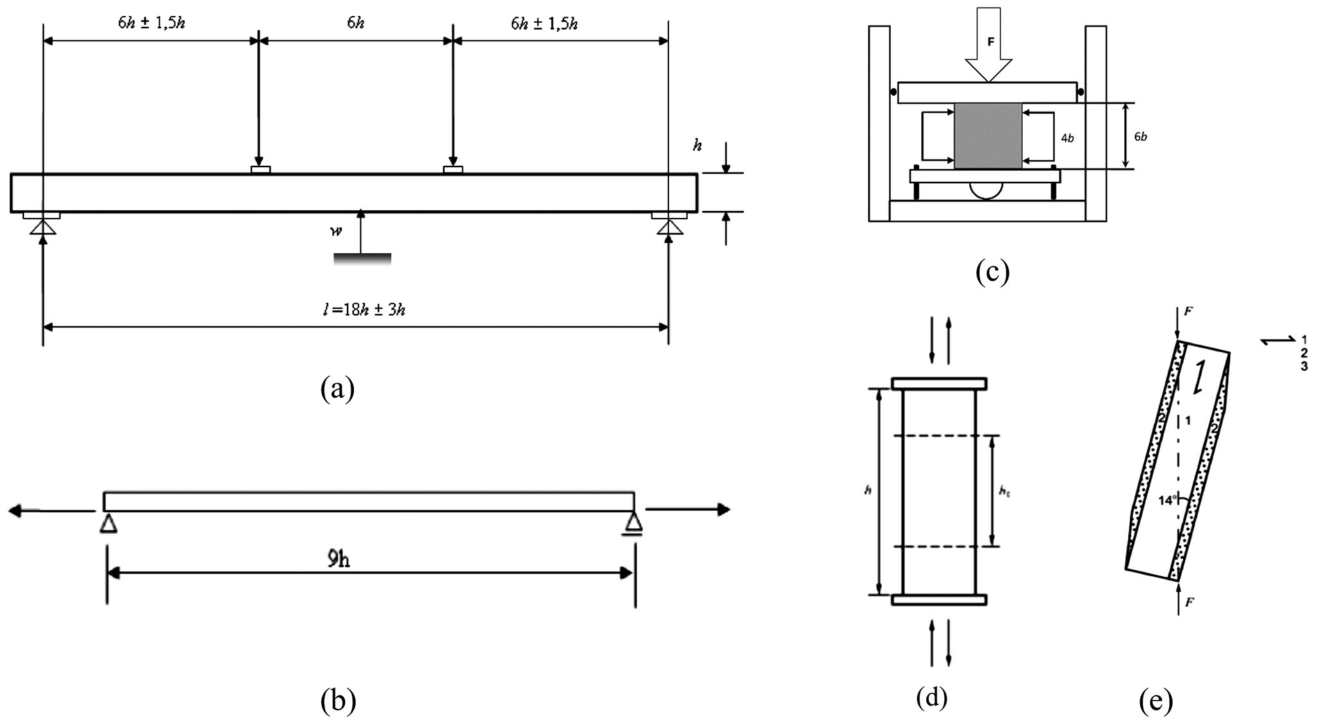

Figure 1. Test set up for bending strength (a), tension parallel to the grain (b), compression parallel to the grain (c), tension and compression perpendicular to the grain (d), and shear strength (e) (EN 408 2010).

2.26%. Due to the higher MC, the shear values are adjusted to a MC of 12%, assuming moderate increase of 2% per 1% MC decrease on the lower edge of the ratios listed by Gerhards (1982) and similar to the factor used by Van de Kuilen and Blass (2005) and Sandhaas *et al*. (2013).

Non-destructive measurements and strength modelling

Non-destructive methods are used to assess timber quality, assign timber to the strength classes and analyse the profiles. Consequently, both visual and machine grading parameters were measured for all timber pieces.

First, dynamic MOE (E_{dyn}) was measured in the laboratory using the longitudinal vibration method. E_{dyn} combines eigenfrequency (f) of the tested specimen, measured using accelerometer, with its density (ρ) and length (l) using Eq. 10.

$$E_{dyn} = 4 \cdot f^2 \cdot l^2 . \rho \qquad (10)$$

The visual grading criteria listed in the German visual grading standard DIN 4074–5 (2008), rules for boards, were measured. Overall, the visual standards contain ten visual criteria for assigning timber to the visual grading classes. In the current study, the criteria single knot, knot cluster, and the presence of the pith were considered for assigning specimens to the visual grades. The single knot (*SK*) is defined as the ratio between the size of the largest knot related to the width of the board (Figure 2a). Knots are measured parallel to the edges and where the cross section of the knots becomes visible. *SK* is calculated by dividing the sum of the measures of all cut surfaces on which the knot occurs by twice the width w (Figure 2a).

The knot cluster (*KC*) is a multiple knot criterion that sums up all *SK* over a length of 150 mm (Figure 2b). The edge knot criterion (the penetration depth of the knot) was not considered for the visual grading, as the use of this criterion is optional for glulam lamellas.

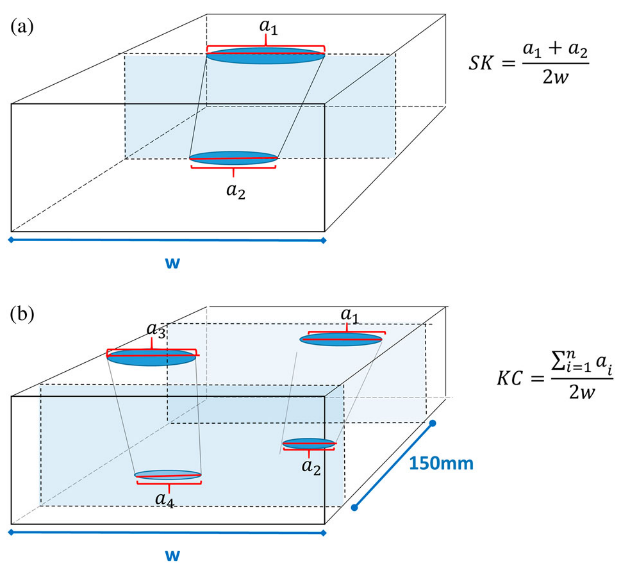

Figure 2. Measurement of the single knot parameter SK (a) and the knot cluster parameter KC (b) according to grading rules for boards specified by the German visual grading standard DIN 4074–1 (2012) and DIN 4074–5 (2008) (Kovryga *et al*. 2019).

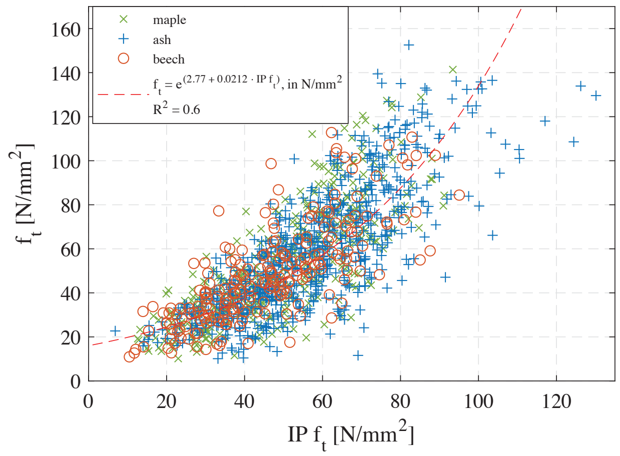

Figure 3. Scatter plot of modelled tensile strength *(IP f_t)* and tensile strength for European ash (*F. excelsior*), European beech (*F. sylvatica*), and maple (*A. spp.*) (*N* = 1338).

To calculate the ratios of tensile strength to both bending and compression strength, the best possible model for tensile strength prediction was selected. The model included the *SK*—the best single predictor of the tensile strength—and E_{dyn}—the best single predictor for the tensile MOE. Eq. 11 represents the model developed.

$$IP\ f_t = exp(a + b \cdot SK + c \cdot E_{dyn}) \qquad (11)$$

In which *IP* f_t is predicted tensile strength in N/mm², *SK* is single knot value [-], E_{dyn} is dynamic MOE in N/mm², and a, b, c are regression constants ($a = 2.82$, $b = -3.0$ and c = 9.2607e-05). Figure 3 shows a scatter plot between modelled tensile strength (*IP* f_t) and tensile strength for ash, maple and beech ($N = 1338$).

Data analysis

The aim of the current analysis is to create optimised profiles for the strength classes with a certain tensile strength to *E* ratio. To conduct the study, the specimens were grouped twice into equally sized groups of 40 specimens each; one time, on the basis of the tensile MOE E_t and one time, based on the tensile strength f_t (Figure 4a). An ideal grading machine is assumed, capable of determining, with 100% accuracy, the tensile MOE in one case and tensile strength in the other case. The 5th percentile of the tensile strength and density of the grouped specimens are calculated using the ranking method. The values of the characteristic tensile strength ($f_{t,0,k}$), $E_{t,0,mean,}$ and characteristic density calculated are plotted against each other (Figure 5 and Figure 6) and compared to the values of the T-Classes listed in EN 338 (2016).

Additionally, the material property profiles based on tensile MOE and tensile strength are compared to the actual grading results. Therefore, beech, ash, and maple specimens were virtually strength-graded. Visual grading was applied according to the German visual grading standard DIN 4074–5 (2008) with visual grades LS10 and LS13. Machine grading was applied using the indicating property (*IP* f_t) calculated using Eq. 11. The machine grading procedure is not applied

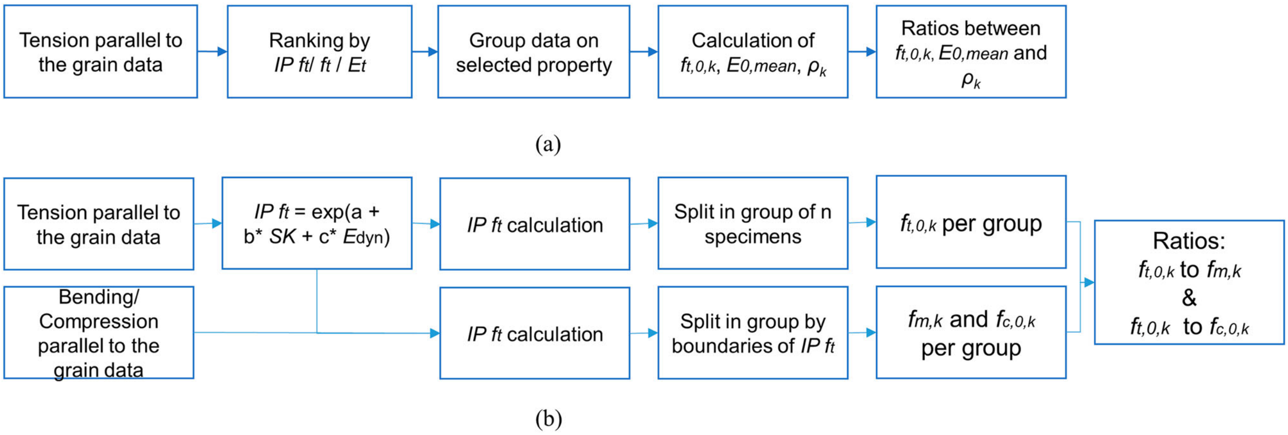

Figure 4. Calculation of the relationships between (a) tensile strength, tensile MOE, and density and (b) tensile strength and bending strength/ compression strength.

to 100% by the machine. Moreover, it combines the machine grading parameter E_{dyn} with the visually measured knottiness. For hardwoods, the available grading machines are not able to detect knots as accurately as the human eye and, therefore, further efforts are required to improve the algorithms (Kovryga *et al.* 2019). The parameters are combined in a grading model that allows the two predictors to compensate each other. This would require the producer to enter the values into the calculation model, which would complicate the grading procedure. In practice, separate threshold values are applied to the grading criteria (E_{dyn} and knottiness) as in the combined visual and machine strength grading introduced by Frese and Blass (2007).

The boundaries for the combined visual and machine strength prediction were determined for grading to a single class and for a combination of classes (multiple classes). In case of grading to a single class, boundaries were increased stepwise by 10 N/mm^2 of *IP* f_t, and all specimens matching or exceeding these threshold values were assigned to the class. The relationship between the material properties was determined for each group of specimens. To simulate grading to a combination of classes, the specimens were grouped by the *IP* f_t in groups of $n_{gr} = 100$ each, and ratios between the material properties were analysed as shown in Figure 4a.

The relationship between tensile strength and compression strength, as well as tensile strength and bending strength, is determined as grouped data. The flow chart in Figure 4b illustrates the selected approach. Therefore, first, *IP* f_t is calculated for tension test, bending test and compression test data. Afterwards, the tension test data are arranged by the *IP* f_t into equally sized groups of 80 specimens each. In the next step, the compression strength and bending strength data are split into groups using determined *IP* f_t boundaries.

Results and discussion

Tensile strength, tensile MOE parallel to the grain and density

First, the tensile strength to tensile MOE ratio is analysed in groups of 40 specimens with tensile MOE ($E_{t,0}$) as indicating property. The relationship between tensile strength and $E_{t,0,mean}$ for ash, beech, and maple match the profiles of the tension classes specified in EN 338 (Figure 5a). Figure 5b shows the relationship between $E_{t,0,mean}$ and ρ_k. According to this figure, ash, beech, and maple species show higher characteristic densities compared to the values stated in EN 338 (2016). However, the density of ash and maple is lower

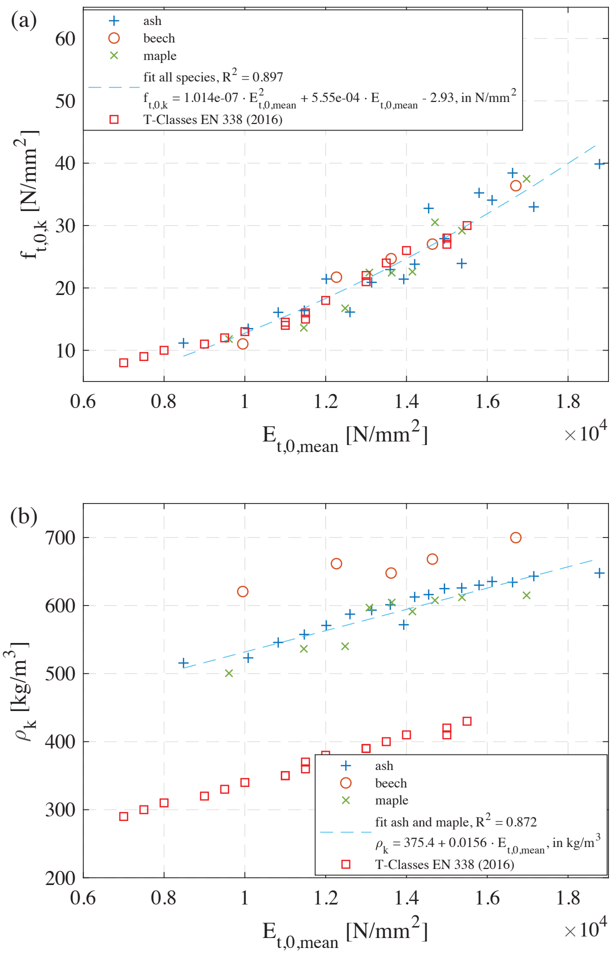

Figure 5. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k in groups of 40 specimens, ranked by $E_{t,0}$ (European ash – *F. excelsior*, European beech – *F. sylvatica*, maple – *A. spp.*).

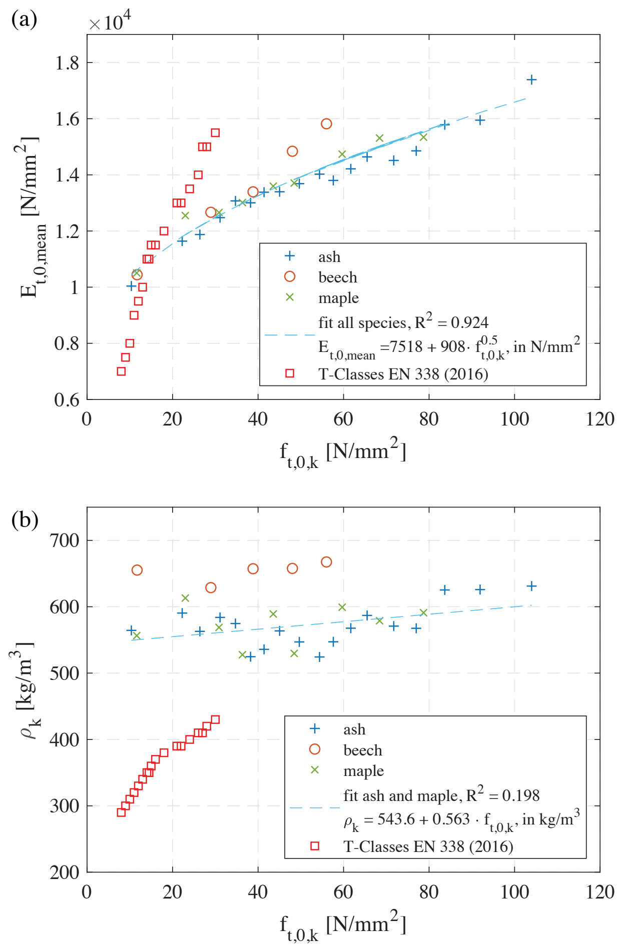

Figure 6. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $f_{t,0,k}$ and ρ_k in groups of 40 specimens, ranked by $f_{t,0}$ (European ash – *F. excelsior*, European beech – *F. sylvatica*, maple – *A. spp.*).

than that of beech. Thus, the characteristic density for the presented hardwoods should at least take on the values of ash and maple; higher density than softwood T-Classes would be a consequence.

If the data are grouped with regard to the tensile strength, the property relationship differs more than that assumed in EN 338. Figure 6 illustrates the relationship between the material properties in this case. The slope of the line between the characteristic strength and tensile MOE is flatter than the line of the T-Classes. Lower mean tensile MOE values can be observed for the same characteristic strength as assumed for the T-Classes. For example, a mean value of tensile MOE parallel to the grain of only 12500 N/mm² is obtained for a characteristic value of tensile strength parallel to the grain of 30 N/mm², compared to 15500 N/mm² listed for the strength class T30.

The relationship between density and tensile strength of the investigated hardwoods does not increase continuously. For ash and maple, the density remains the same, at a level of 600 kg/m³, with some fluctuations down to 550 kg/m³.

For defining the class values, the relationship between tensile MOE and strength should be considered, and, whether strength or MOE should be the most important grading parameter for the hardwoods presented here.

The effect of grading on the major characteristic properties

To derive the strength class profiles, the material properties of both visually and combined visually – machine strength graded timber are analysed. Figure 7 illustrates $E_{t,0,mean}$ to $f_{t,0,k}$ and $E_{t,0,mean}$ to ρ_k ratios for the visually graded ash, beech, and maple specimens. $E_{t,0,mean}$ to $f_{t,0,k}$ matches the ratios for the softwood T-Classes (Figure 7a). Characteristic values of visually graded hardwood specimens ($E_{t,0,mean}$ and $f_{t,0,k}$) range within the values covered by the strength class system for softwoods. Ash, beech, and maple boards, assigned to the highest visual grade LS13, reveal mechanical properties equivalent to the strength class T28 ($f_{t,0,k}$ = 28 N/mm² and $E_{t,0,mean}$ = 15000 N/mm²) as a maximum. The $f_{t,0,k}$ and $E_{t,0,mean}$ values in T-Classes range up to 30 and 15500 N/mm² respectively.

The ρ_k to $E_{t,0,mean}$ ratio is, as expected, above the values for the T-Classes. Nevertheless, the ratio does not seem to depend on the visual grading procedure. For ash graded to LS13, the density is even lower than the specimens assigned to LS10. For beech specimens, the density increases only slightly between LS10 and LS13. These results comply with the fact that the density of hardwoods cannot be estimated visually, for instance by analysis of growth ring width.

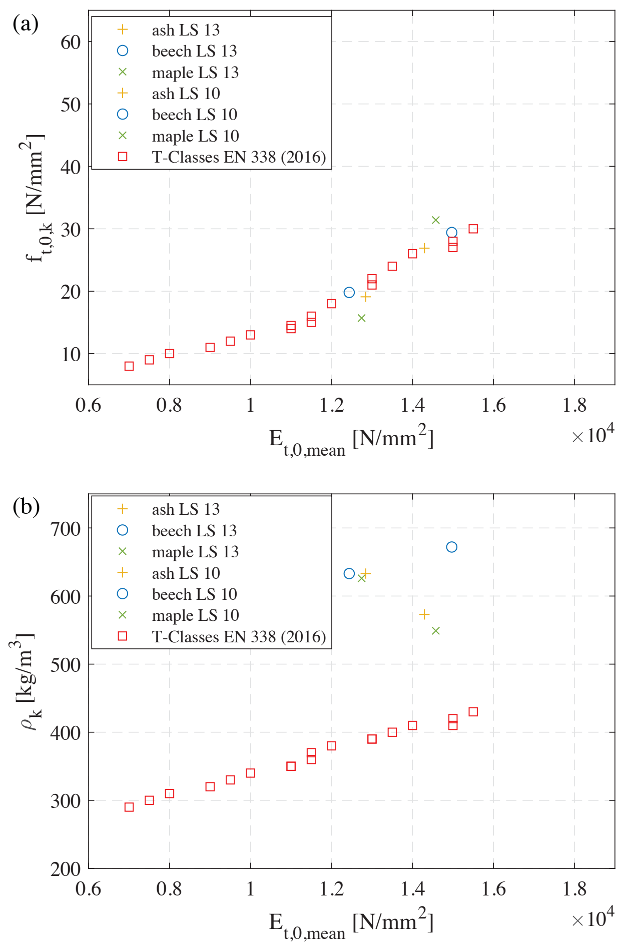

Figure 7. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k for the visually graded timber of European ash (*F. excelsior*), European beech (*F. sylvatica*), and maple (*A. spp.*).

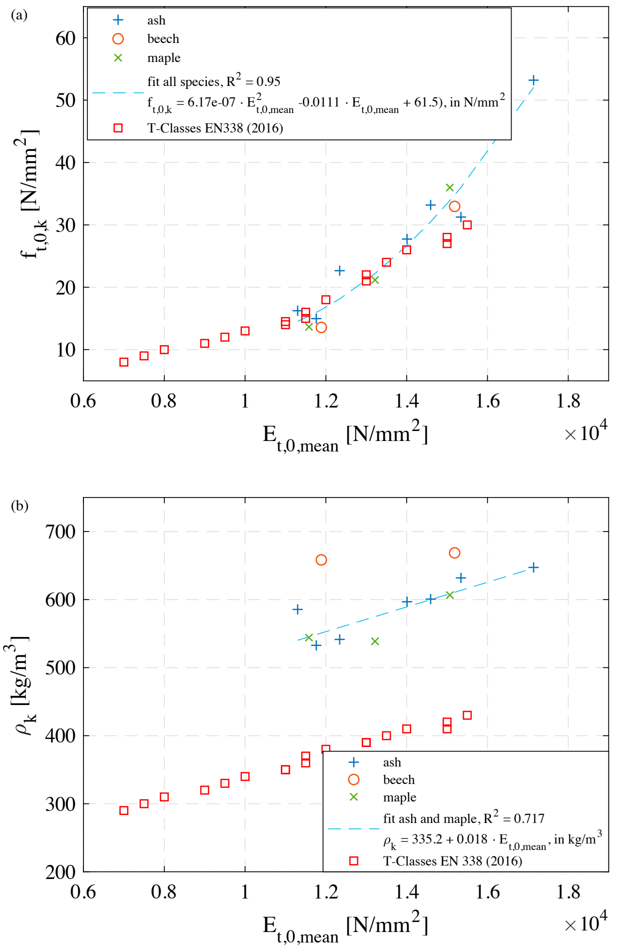

Figure 8. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k in groups of 100 specimens, ranked by *IP* f_t (European ash – *F. excelsior*, European beech – *F. sylvatica*, maple – *A. spp.*).

Therefore, a single density value for all strength classes, to which visually graded hardwoods might be assigned, is a possible solution, thereby avoiding that for various species with similar strength and stiffness values separate density values need to be declared.

For a combined visual and machine strength prediction, the relationship between $f_{t,0,k}$ and $E_{t,0,mean}$ is closer to the T-Classes. This is especially true for specimens graded to a combination of classes (Figure 8a). For groups of hardwood boards with $f_{t,0,k}$ below 28 N/mm^2, $f_{t,0,k}$ to $E_{t,0,mean}$ ratio is close to the T-Classes. However, for the higher tensile MOE $E_{t,0,mean}$ values, the tensile strength increases with the higher slope of the regression line. This increase is similar to the behaviour of tensile strength/tensile MOE ratio obtained for grouping by tensile strength (Figure 6a). As *IP* f_t predicts both tensile strength ($R^2 = 0.6$) and tensile MOE ($R^2 = 0.57$) with high accuracy, the tensile strength/tensile MOE ratio of the combined visual and machine grading is similar to the ratios derived on the basis of tensile MOE and tensile strength.

Grading to a single class (Figure 9a) shows similar ratios compared to the grading to multiple classes (Figure 8a). The presence of specimens with high *IP* f_t in classes with lower characteristic strength allows to increase the $E_{t,0,mean}$ compared to grading to multiple classes (Figure 8a).

The characteristic density of the machine-graded hardwoods increases with tensile MOE (Figure 8b). The used *IP* f_t includes density as one of the inputs for the E_{dyn} calculation. Therefore, an increase in density values should be allowed for the higher strength classes, feasible for the machine strength grading using the combined approach.

Tensile strength to bending strength ratio

In the current study, the tensile to bending strength ratio was examined for ash specimens of equal dimensions tested in tension and in bending. Figure 10 shows the tensile strength to bending strength ratio for equally sized timber grouped by the *IP* f_t. The equation fitted to the data, shown in the figure, shows a higher slope than the one for the T-Classes. The underlying ratio is close to the one of the D-Classes, conservatively determined for the bending strength and not for the tensile strength.

Tensile strength to compression strength ratio

Figure 11 shows the ratio between tensile and compression strength obtained for the combined beech and ash data. The estimated equation leads to higher compression strength values than the ones listed in EN338 (2016). For the higher strength classes, the fitted equation converges to the one for the softwood T-Classes. If the species are examined separately, both hardwood species tend to behave in a similar way, even though ash seems to have a slightly higher f_c/f_t ratio. For simplicity reasons, the equation for softwoods could be applied to the medium-density hardwoods as well.

Properties perpendicular to the grain direction

Figure 12 shows the relationship between density and tensile and compression strength perpendicular to the grain for ash and beech for the data of Hunger and Van de Kuilen (2015) and Westermayr *et al.* (2017). No correlation between tensile strength and density, nor between compression strength and density for a combination of two species could be found. A correlation of 0.462 between compression strength and density can only be reported for ash. The density values for ash show a wide variation when compared to the beech.

The missing correlation between the tensile strength perpendicular to the grain and density does not allow specifying a distinct value for each class. Consequently, the same value for all classes is sufficient. For the present data, the characteristic values for ash and beech are 3.40 and 3.48 N/mm^2, respectively and exceed the values for solid wood listed in EN 338. Therefore, a single value of 3.4 N/mm^2 is proposed for the medium-density hardwoods presented.

The weak correlation between density and compression strength does not allow a significant conclusion to be drawn on the relationship between these variables. By keeping in mind the low feasibility of visual grading to distinguish between different density levels, it is essential to have the same characteristic strength value for the compression strength perpendicular to the grain. With the data

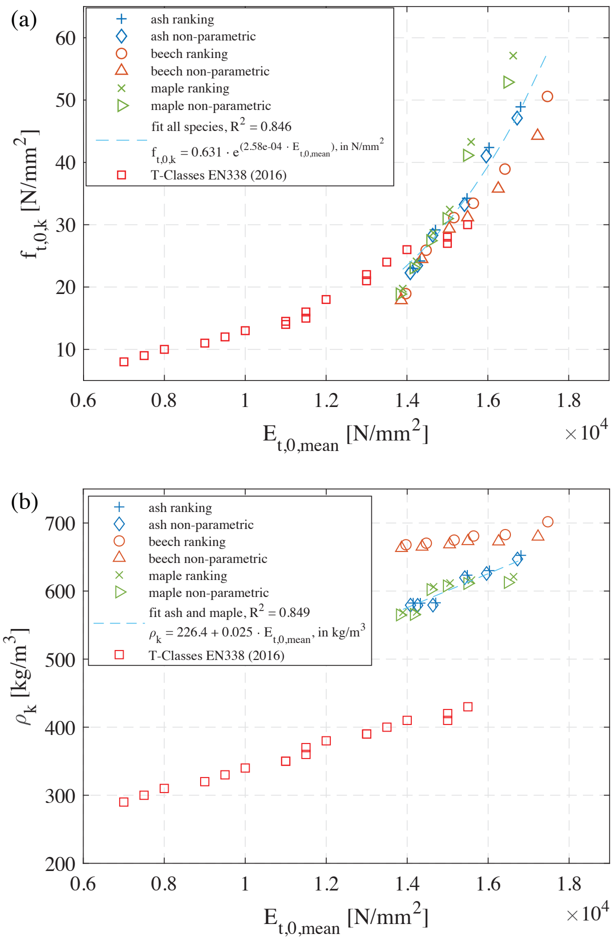

Figure 9. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k for the combined visual and machine strength grading of the medium-density European hardwoods European ash (*F. excelsior*), European beech (*F. sylvatica*), and maple (*A. spp.*) into one class.

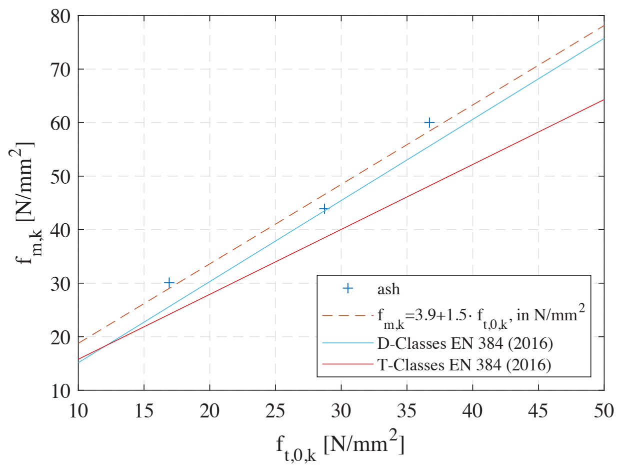

Figure 10. Relationship between tensile and bending strength for data in groups of 80 specimens, ranked by *IP* f_t . Ratio is based on 324 bending and 274 tension test specimens of European ash (*F. excelsior*).

of Hunger and Van de Kuilen (2015), the characteristic compression strength values are 6.67 and 6.77 N/mm^2 for ash and beech, respectively. The results are comparable to the values reported by Hübner (2013) on beech and ash glulam. A single characteristic strength value for all classes—6.6 N/mm^2—is proposed for the standard.

The ratio of $E_{t,0,mean}$ to $E_{90,mean}$ specified in EN 338 for softwood T-Classes (30) and hardwood D-Classes (15) can be compared to the values of ungraded timber for both the compression and the tensile test perpendicular to the grain. The ratio derived from test values ranges from 14.65–16.0 for $E_{t,0,mean}$ to $E_{t,90,mean}$ and 12.4–13.8 for $E_{t,0,mean}$ to $E_{c,90,mean}$. The values specified for hardwood D-Classes seem applicable to temperate hardwoods tested in tension.

Shear strength

Figure 13 shows, for ash, beech, and oak, the relationship between shear strength and density both adjusted to 12% MC. Over the entire scatter of the three hardwood specimens, a weak correlation between density and shear strength can be found ($r = 0.234$). A stronger relationship can be found within the individual wood species with the coefficient of correlation of 0.382, 0.396–0.454 for beech, oak, and ash, respectively. In this case, however, the correlation overlays high variation in shear strength values for the same density level. Exemplarly, for denser ash specimens (>700 kg/^{3}), the shear strength values range between 10 and 16.6 N/mm^2. The coefficient of variation for shear strength ranges from 0.07 for oak to 0.14 for ash. If the wood species ash, beech, and oak are observed as a single sample, the variation in shear strength values is higher with the coefficient of variation of 0.178.

In Figure 13, individual scatter characteristics of the selected wood species are observable. So, the shear strength values for oak scatter over the density below the ones of ash and beech. For a similar characteristic density level, oak shows lower characteristic shear strength ($f_{v,k} = 7.5$ N/mm^2) compared to beech with 10.7 N/mm^2. The characteristic shear strength values are calculated using log-normal distribution in accordance with the JCSS Probabilistic Model Code (2006) which was confirmed with the test data. Differences in shear strength between the various species may be caused by species-specific characteristics at anatomical level, such as the presence of rays and the pore structure (ring porous, semi ring porous or diffuse porous). An additional bias is given by the difference in the test setup, as the height of beech and ash samples is smaller than that required in EN 408. Furthermore, fissures (cracks, etc.) and growth ring orientation also affect the shear strength and may differ between samples.

The weak correlation between density and shear strength coupled with the high variation in the property values, as well as the occurring bias does not allow specifying a reliable relationship between these variables for the assignment of shear strength values. Furthermore, visual grading cannot distinguish different densities and consequently does not allow utilizing the relationship between density and shear strength. See also Van de Kuilen *et al.* (2017). Therefore, a single constant value (7.5 N/mm^2) based on the lowest characteristic shear strength of all samples is proposed for the strength class profiles.

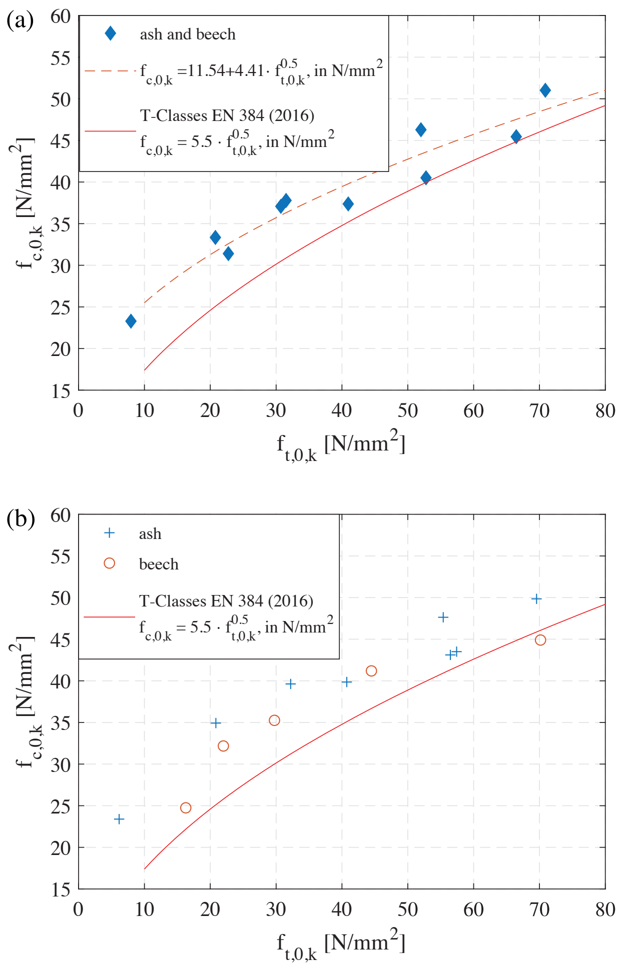

Figure 11. Relationship between characteristic tensile strength and compression strength for (a) joint European beech (*F. sylvatica*) and European ash (*F. excelsior)* data (grouped by 80 specimens) and (b) European beech (*F. sylvatica)* and European ash (*F. excelsior*) separately (grouped by 40 specimens), ranked by *IP* f_t.

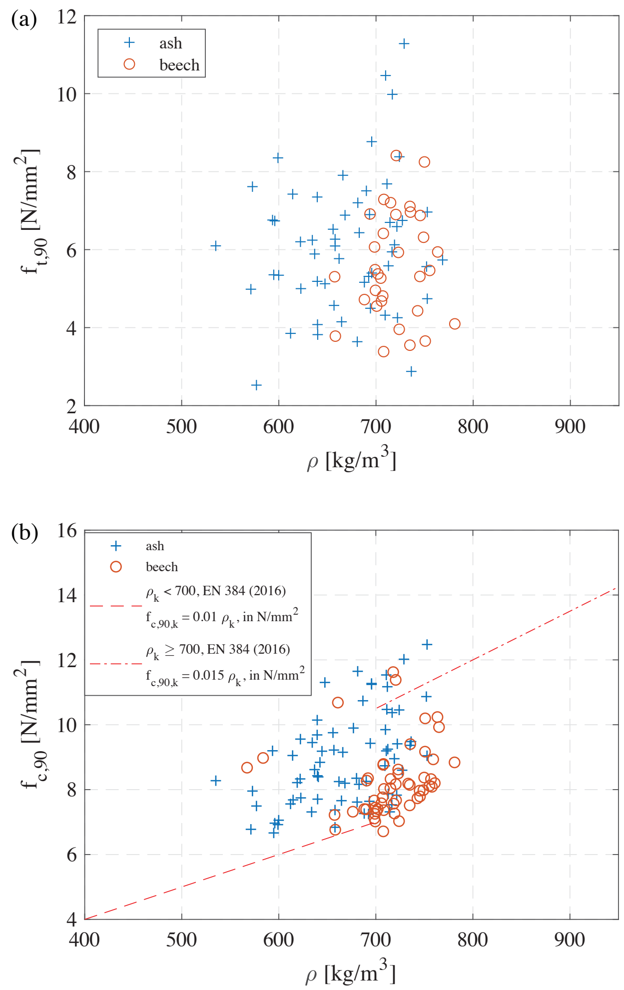

Figure 12. Relationship between (a) $f_{t,90}$ and ρ, and (b) between $f_{c,90}$ and ρ for European ash (*F. excelsior*) and European beech (*F. sylvatica*).

Proposal for tensile strength profiles for hardwoods

Based on the relationships analysed, tensile strength classes for hardwoods were proposed and named DT-Classes, where "D" stands for hardwoods ("deciduous") and "T" for tension. Table 4 lists a selection of new classes, which could be extended in both directions using the relationships derived. There are three options for defining the ratio between $E_{t,0,mean}$ to $f_{t,0,k}$. The first option, shown in Figure 5, gives $f_{t,0,k}$ over measured $E_{t,0,mean}$, the second option, shown in Figure 6, gives $E_{t,0,mean}$ over measured $f_{t,0,k}$, while the third option is calculated as the ratio between $E_{t,0,mean}$ to $f_{t,0,k}$ based on modelled tensile strength (*IP* f_t). The third option is proposed in the strength class, as it optimizes the assignment to a strength class, and both strength and stiffness are optimised. This also is a method of relevance for practice, as the design of glulam will be governed by both strength and stiffness. Furthermore, tensile strength and stiffness can be achieved by means of the combined visual grading only. The resulting $f_{t,0,k}$ increases with a higher slope for a characteristic strength above 30 N/mm², as illustrated in Figure 14.

The proposed DT-Classes are to be clearly distinguished from the D-Classes of EN 338. The D-Classes are defined for bending applications with bending strength and bending MOE as the major characteristic property, whereas characteristic tensile strength is calculated on the safe side assuming the tension strength to bending strength ratio of 0.6. Therefore, for the given MOE $E_{0,mean}$ value, the tensile strength in D-Classes is lower. Additionally, the D-Classes cover tropical hardwoods with high characteristic density, which makes an assignment of medium-density European hardwoods to classes above D50 ($f_{m,k} = 50$ N/mm², $f_{t,0,k} = 30$ N/mm²) difficult due to the requirement on characteristic density ($\rho_k = 620$ kg/m³).

If the proposed classes are compared to the literature values in Figure 14, for the highest visual grades of birch, beech, and chestnut, the derived profiles match the properties better than the current T-Classes. In addition, higher classes than T30 are possible. However, if the existing system of T-Classes is used for hardwoods, $E_{t,0}$ will become the grade-limiting property, whereas the strength requirement is generally fulfilled. In cases where one of the properties is generally fulfilled, the timber properties are utilised inefficiently. This can be observed from both the data calculated and the values from

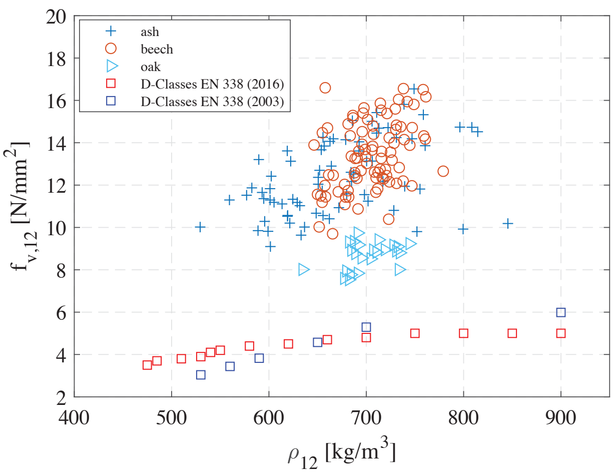

Figure 13. Relationship between the ρ_{12} and $f_{v,12}$ for medium-density European hardwoods ash (*F. excelsior*), beech (*F. sylvatica*) and osk (*Q. spp.*). All values are adjusted to 12% MC.

the literature. Therefore, the proposed table is based on an optimised ratio for $E_{t,0,mean}$ and $f_{t,0,k}$.

The selected density profile follows the constant characteristic density value for the strength classes below DT30. Above DT30, the density increases, following the relationship for the machine-graded timber, which reflects the fact that visual grading is not able to distinguish between the different density values. The estimated profiles are shown in Figure 14b in comparison to the existing classes and literature values. For tensile strengths below 30 N/mm^2, the defined threshold value for the characteristic density matches the values for birch and beech, whereas the value is too high for the characteristic density of chestnut.

This also shows clearly that determining a single density value for all medium-density hardwood species might not be easy. The characteristic density of the timber analysed here shows a high variation, ranging from 520 kg/m^3 for LS13 maple to 660 kg/m^3 for LS13 beech. For LS13 maple tested in bending, characteristic values as high as 590 kg/m^3 were reported by Glos and Torno (2008b). For chestnut, a characteristic density of 510 kg/m^3 was found by Nocetti *et al.* (2010). Consequently, a separate declaration of the density for each combination of species or grades would be the best solution. Frühwald and Schickhofer (2005) have already suggested to make density an optional, indicative parameter, rather than a mandatory one, as is currently required for the design of connections.

The relationships between the material properties are only derived from the medium-density hardwoods ash, beech, and maple from Central Europe. The relationship should be verified on other relevant hardwood specimens, such as oak and chestnut.

Conclusion

In this paper, material properties of the medium-density hardwoods European ash (*F. excelsior*), European beech (*F. sylvatica*), and maple (*A. spp.*) tested in tension are analysed. The material property profiles have been examined with regard to tensile MOE, tensile strength, visual grading, and combined visual and machine strength prediction, allowing for creating profiles which fit the properties of the selected hardwoods in the best way. These profiles have been incorporated into a proposed system of tensile strength classes for hardwoods (DT-Classes) presented here. The DT-Classes are a viable addition to the hardwood bending strength classes (D-Classes). For the same tensile strength, DT-Classes indicate higher tensile MOE values parallel to the grain compared to D-Classes.

On the basis of the research, the following can be concluded:

- The presented DT-Classes allow efficient utilisation of their properties as lamellas for glulam production tailored to the material properties of ash, beech, and maple. The proposed DT-Classes include higher classes, up to the strength class DT50, with a characteristic tensile strength of 50 N/mm^2 and tensile MOE $E_{t,0,mean}$ of 17000 N/mm^2, which are required for glulam beams of strength class GL48 and beyond. The proposed relationship between tensile strength and tensile MOE matches the test values reported for a variety of European hardwoods. However, additional validation on other European hardwood species relevant for glulam, such as oak and chestnut is suggested.
- Classes with property values of DT30 can be reached by visual grading. For those classes, either T-Classes or DT-Classes may be used. DT-Classes show the advantage of higher derived

Table 4. Proposed tensile strength classes for medium-dense European hardwoods (DT-Classes).

	Property	DT22	DT24	DT28	DT30	DT34	DT38	DT42	DT46	DT50
Strength properties [N/mm^2]	$f_{m,k}$ [a]	37	40	46	49	55	61	67	73	79
	$f_{t,0,k}$	22	24	28	30	34	38	42	46	50
	$f_{t,90,k}$ [b]	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	$f_{c,0,k}$ [c]	32	33	35	36	37	39	41	42	43
	$f_{c,90,k}$ [d]	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
	$f_{v,k}$ [e]	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Stiffness properties [N/mm^2]	$E_{t,0,mean}$	13000	13500	14000	14500	15000	15500	16000	16500	17000
	$E_{90,mean}$ [f]	810	830	880	930	1000	1030	1070	1100	1130
Density [kg/m^3]	ρ_k	550	550	550	550	610	610	620	630	640
	ρ_{mean} [g]	660	660	660	660	730	730	740	750	760

[a] $f_{m,k} = 3.9 + 1.5 \cdot f_{t,0,k}$ in N/mm^2
[b] $f_{t,90,k} = 3.4$ N/mm^2
[c] $f_{c,0,k} = 11.54 + 4.41 \cdot f_{t,0,k}^{0.5}$ in N/mm^2
[d] $f_{c,90,k} = 6.6$ N/mm^2
[e] $f_{v,k} = 7.5$ N/mm^2
[f] $E_{90,mean} = E_{0,mean}/15$ in N/mm^2 (EN 384 2016)
[g] $\rho_{mean} = 1.2 \cdot \rho_k$ in kg/m^3 (EN 384 2016)

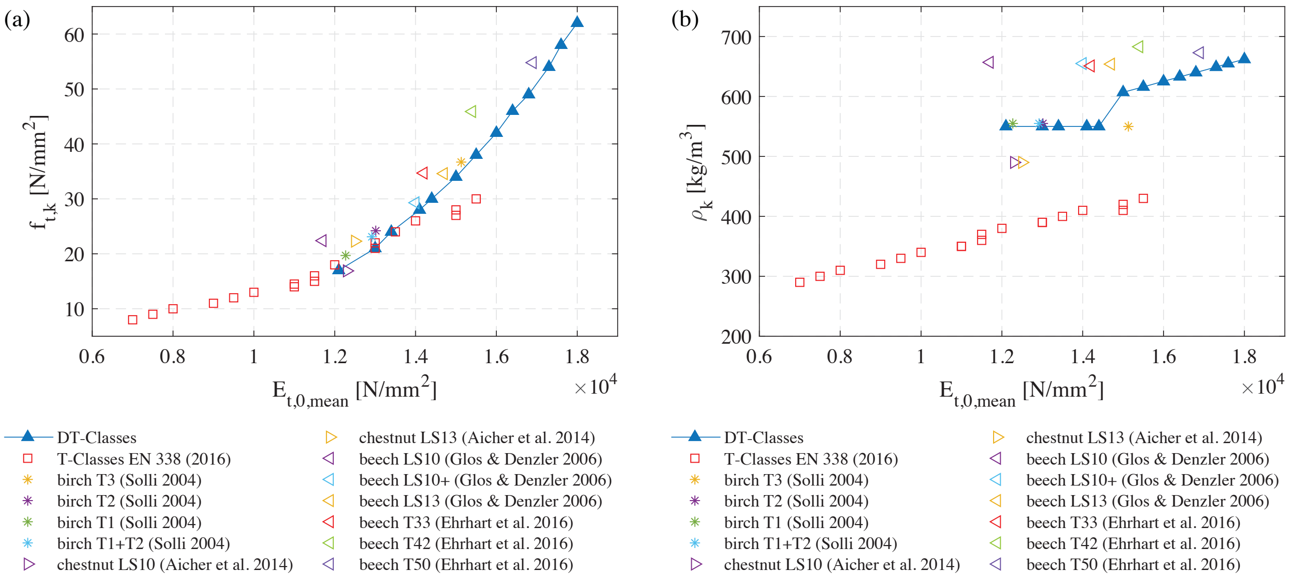

Figure 14. Relationship between (a) $E_{t,0,mean}$ and $f_{t,0,k}$ and (b) between $E_{t,0,mean}$ and ρ_k for the proposed DT-Classes for hardwoods in comparison to the T-classes for softwoods and values for European beech (*F. sylvatica*), birch (*Betula spp.*) and sweet chestnut (*Castanea sativa*) published in literature.

properties (properties perpendicular to the grain, shear strength). Classes beyond DT30 can only be reached by methods allowing higher strength and stiffness prediction. Either machine grading or combined visual and machine grading, which incorporates knot measurements and measurement of the dynamic modulus of elasticity, are qualified for assigning boards to the higher classes.

- Setting a characteristic value for density remains a challenging task. High variation in density properties between the hardwoods and the fact that the density of hardwoods cannot be estimated using visual grading rules, compromises the use of density as one of the major characteristic properties. Having in mind that the density affects the embedment strength of timber and hence, is an important parameter in the design of connections, the possibility of declaring density separately from the strength classes should be investigated.
- The ratio of bending strength to tensile strength has been analysed for ash and the ratio of compression strength to tensile strength for both ash and beech. This ratio is higher than for softwood T-Classes. For reasons of simplicity, the relationships listed in the T-Classes for softwoods could be used for hardwoods.
- Based on the available data on compression and tension properties perpendicular to the grain and shear strength, constant $f_{t,90,k}$, $f_{c,90,k}$, $f_{v,k}$ values for all strength classes are proposed as a basis for the introduction of DT-Classes. The proposed values of $f_{t,90,k}$ with 3.4 N/mm^2, $f_{c,90,k}$ with 6.6 N/mm^2, $f_{v,k}$ with 7.5 N/mm^2 are higher compared to the values of bending strength classes for hardwoods (D-Classes) listed in EN 338 (2016).

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References

Aicher, S., Christian, Z., and Dill-Langer, G. (2014) Hardwood Glulams – Emerging timber products of superior mechanical properties. In Proc. of 13th World Conference on Timber Engineering (WCTE 2014), Quebec, Canada.

ASTM D1990. (2000) Standard practice for establishing allowable properties for visually-graded dimension lumber from in-grade tests of full-size specimens.

Bacher, M. and Krzosek, S. (2014) Bending and tension strength classes in European standards. *Forestry and Wood Technology*, 88, 14–22.

BAFU (2015) *Jahrbuch Wald und Holz 2015* (Bern: Bundesamt für Umwelt), Umwelt-Zustand Nr. 1520.

Blass, H. J., Denzler, J. K., Frese, M., Glos, P. and Linsenmann, P. (2005) *Materialkennwerte von Eschenholz für den Einsatz in Brettschichtholz* (Karlsruhe: Universitätsverlag Karlsruhe). (in German)

Bundesministerium für Ernährung und Landwirtschaft (BMEL) (2015) The Forests in Germany - Selected Results of the Third National Forest Inventory.

Burger, N. and Glos, P. (1997) Verhältnis von Zug- zu Biegefestigkeit bei Vollholz. *Holz als Roh- und Werkstoff*, 56 (6), 345–350. (in German). https://doi.org/10.1007/s001070050245.

Denzler, J. K. (2012) Harmonised tensile strength classes. Paper 45-5-1. In Proceedings of the 45th CIB-W18 Meeting, Växjö, Sweden.

Denzler, J. K. and Glos, P. (2007) Determination of shear strength values according to EN 408. *Materials and Structures*, 40(1), 79–86. DOI: 10.1617/s11527-006-9199-4.

DIN 4074-1 (2012) Sortierung von Holz nach der Tragfähigkeit - Teil 1: Nadelschnittholz. DIN, Berlin. (in German).

DIN 4074-5 (2008) Sortierung von Holz nach der Tragfähigkeit - Teil 5: Laubschnittholz. DIN, Berlin. (in German).

Ehrhart, T., Fink, G., Steiger, R. and Frangi, A. (2016) Strength grading of European beech lamellas for the production of GLT & CLT. Paper 49-5-1. In *Proc. of the 49th INTER & CIB Meeting*, Graz, Austria.

EN 1194 (1999) *Timber Structures - Glued Laminated Timber - strength Classes and Determination of Characteristic Values* (Brussels: CEN European Committee for Standardization).
EN 13183-1 (2002) *Moisture Content of a Piece of Sawn Timber - Part 1: Determination by Oven dry Method* (Brussels: CEN European Committee for Standardization).
EN 14080 (2005) *Timber Structures. Glued Laminated Timber and Glued Solid Timber*. Requirements (Brussels: CEN European Committee for Standardization).
EN 14080 (2013) *Timber Structures. Glued Laminated Timber and Glued Solid Timber. Requirements* (Brussels: CEN European Committee for Standardization).
EN 14081-4 (2009) *Timber Structures - Strength Graded Structural Timber with Rectangular Cross Section - Part 4: Machine Grading - Grading Machine Settings for Machine Controlled Systems* (Brussels: CEN European Committee for Standardization).
EN 1912 (2012) *Structural Timber. Strength Classes. Assignment of Visual Grades and Species* (Brussels: CEN European Committee for Standardization).
EN 338 (2003) *Structural Timber – Strength classes* (Brussels: CEN European Committee for Standardization).
EN 338 (2016) *Structural Timber – Strength Classes* (Brussels: CEN European Committee for Standardization).
EN 384 (2010) *Structural Timber – Determination of Characteristic Values of Mechanical Properties and Density* (Brussels: CEN European Committee for Standardization).
EN 384 (2016) *Structural Timber - Determination of Characteristic Values of Mechanical Properties and Density* (Brussels: CEN European Committee for Standardization).
EN 408 (2010) *Timber Structures. Structural Timber and Glued Laminated Timber. Determination of Some Physical and Mechanical Properties* (Brussels: CEN European Committee for Standardization).
Frese, M. and Blass, H.J. (2007) Characteristic bending strength of beech glulam. *Materials and Structures*, 40, 3–13, RILEM. https://doi.org/10.1617/s11527-006-9117-9.
Frühwald, A., Ressel, J. B., Bernasconi, A., Becker, P., Pitzner, B., Wonnemann, R., Mantau, U., Sörgel, C., Thoroe, C. and Dieter, M.. (2003) "Hochwertiges Brettschichtholz aus Buchenholz." *Res Rep Bundesforschungsanstalt für Forst-und Holzwirtschaft*, Hamburg. (in German).
Frühwald, K. and Schickhofer, G. (2005) Strength grading of hardwoods. *In Proceedings of the 14th International Symposium on Nondestructive Testing of Wood*, 198–210.
Galligan, W.L., Gerhards, C.C., Ethington, R.L. (1979) Evolution of tensile design stresses for lumber. USDA, Forest Service, Forest Products Laboratory, Report FPL-28.
Gerhards, C. C. (1982) Effect of moisture content and temperature on the mechanical properties of wood: An analysis of immediate effects. *Wood and Fiber Science*, 14 (1), 4–36.
Glos, P. and Denzler, J.K. (2006) Allocation of central European hardwoods into EN 1912. Paper 39-6-1. *In Proc. of the 39th CIB-W18 Meeting*, Florence, Italy.
Glos, P. and Lederer, B. (2000) Sortierung von Buchen- und Eichenschnittholz nach der Tragfähigkeit und Bestimmung der zugehörigen Festigkeits- und Steifigkeitskennwerte. München: Holzforschung München, Technische Universität München, Bericht Nr. 98508, 125 pp. (in German).
Glos, P. and Torno, S. (2008a) Allocation of ash and poplar of German origin to EN 1912. München: Holzforschung München, Technische Universität München, TG1 / 0508 / 16 (Report 06517_B).
Glos, P. and Torno, S. (2008b) Allocation of maple of German origin to EN 1912. München: Holzforschung München, Technische Universität München, TG1 /1108 / 26 (Report 06517_B).
Green, D. W. (2005) Grading and properties of hardwood structural Lumber. Chapter 4. In R. J. Ross, and J. R. Erickson(eds) *Undervalued Hardwoods for Engineered Materials and Components* (Madison: Forest Products Society), pp. 31–55.
Hausegger, G. (2017) Waldland Österreich. Available at: http://www.proholz.at/co2klimawald/waldland-oesterreich, checked on 9/8/2017 at 11:40. (in German).
Hübner, U. (2013) Mechanische Kenngrößen von Buchen-, Eschen- und Robinienholz für lastabtragende Bauteile. Dissertation. Technische Universität Graz.
Hunger, F. and Van de Kuilen, J.W.G. (2015) Festigkeitsprofile von heimischen Laubhölzern. München: Holzforschung München, Technische Universität München, Report Nr. 13508/ "X40". (in German).
JCSS (2006) Probabilistic Model Code - Part 3.5: Properties of timber.
Kovryga, A., Schlotzhauer, P., Stapel, P., Militz, H. and Van de Kuilen J.W.G. (2019) Visual and machine strength grading of European ash and maple. Accepted for publication in *Holzforschung*. doi:10.1515/hf-2018-0142
Nocetti, M., Bacher, M., Brunetti, M., Crivellaro, A. and Van de Kuilen, J.W.G. (2010) Machine grading of Italian structural timber: preliminary results on different wood species. In *Proc. of 11th World Conference on Timber Engineering (WCTE 2010)*, Riva del Garda, Italy.
Pautasso, M., Aas, G., Queloz, V., Holdenrieder, O. (2013) European ash (Fraxinus excelsior) dieback – A conservation biology challenge. *Biological Conservation*, 158, 37–49. DOI: 10.1016/j.biocon.2012.08.026.
Ranta-Maunus, A., Denzler J.K., Stapel P. (2011) Strength of European timber: Part 2. Properties of spruce and pine tested in Gradewood project. Vol 179 of VTT Working Papers, VTT, Finland.
Ravenshorst, G. J. P. (2015) Species independent strength grading of structural timber. PhD thesis (Delft:Technische Universiteit Delft).
Ravenshorst, G., Gamper, N., Vries, P. de and Van de Kuilen, J. W. G. (2016). Determination of the shear strength of tropical hardwood timber. In Proc. of 14th World Conference on Timber Engineering (WCTE 2016), Vienna, Austria, August 23–25. Wien: TU Verlag.
Sandhaas, C., Ravenshorst, G. J. P., Blass, H. J. and Van de Kuilen, J. W. G. (2013) Embedment tests parallel-to-grain and ductility aspects using various wood species. *Eur. J. Wood Prod*, 71 (5), 599–608. DOI: 10.1007/s00107-013-0718-z.
Solli, K. H. (2004) Tensile strength of nordic birch. Paper 37-6-1. In *Proc. of the 37th CIB-W18 Meeting*, Edinburgh, Scotland, 2004.
Steiger R. (1996) Mechanische Eigenschaften von Schweizer Fichten-Bauholz bei Biege-, Zug-, Druck- und kombinierter M/N-Beanspruchung. Institut für Baustatik und Konstruktion, Bericht Nr. 221, ETH Zürich. (in German).
Steiger, R. and Arnold, M. (2009) Strength grading of Norway spruce structural timber: Revisiting property relationships used in EN 338 classification system. *Wood Science and Technology*, 43 (3), 259–278. doi:10.1007/s00226-008-0221-6
Van de Kuilen, J. W. G. and Blass, H. J. (2005) Mechanical properties of azobé (Lophira alata). *Holz als Roh- und Werkstoff*, 63 (1), 1–10. DOI: 10.1007/s00107-004-0533-7.
Van de Kuilen, J.-W. G. and Torno, S. (2014) Materialkennwerte von Eschenholz für den Einsatz in Brettschichtholz. München: Holzforschung München, Technische Universität München, Report Nr. 11508. (in German).
Van de Kuilen. J.W.G, Gard, W., Ravenshorst, G., Antonelli, V., Kovryga, A. (2017) Paper 50-6-1. In Proc. *of the 50th INTER & CIB Meeting*, Kyoto, Japan, 2017.
Westermayr, M., Hunger, F. and Van de Kuilen, J. W. G. (2017) Strength and stiffness perpendicular to the grain of ash (Fraxinus e.) and beech (Fagus s.) in comparison to spruce (Picea a.). In Proc. Of 6th International Scientific Conference on Hardwood Processing 2017 (ISCHP 2017), Lahti, Finland, September 25–28. Helsinki: natural Resources Institute Finland (Luke), 52–59.

II Paper II - Visual and machine strength grading of European ash and maple for glulam applications

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Visual and machine strength grading of European ash and maple for glulam application

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Abstract: Medium dense hardwoods (HWs) show higher tensile strength (TS) values than softwoods (SWs). These advantages cannot be utilised effectively because HW grading is not well developed. The aim of the present paper was to analyse the utilisation potential of European ash (*Fraxinus* spp.) and maple (*Acer* spp.) grown in Central Europe, which were graded by different methods. The visual grading characteristics of 869 HW boards were determined and the dynamic modulus of elasticity (MOE_{dyn}) and X-ray attenuation (XRA) were measured by an industrial scanner. The specimens were subsequently tested in tension according to EN 408:2010 and according to German visual grading rules show strength values of 28 MPa and 30 MPa, respectively. Machine strength grading and for a combination of manually assessed boards and MOE_{dyn} give rise to higher strength data. MOE_{dyn}, in particular, results in lamella data with 62 MPa for ash and 42 MPa for maple. There is good agreement with recently presented HW tensile profiles. Machine grading with a multisensor system allows better strength prediction compared to the MOE_{dyn} or visual strength grading. Best performance is achieved by a combined grading approach.

Keywords: dynamic MOE, glulam, grading of hardwoods, hardwoods, machine grading, mechanical properties of hardwoods, multisensor system, optimisation, strength profiles, tensile strength, visual strength grading, X-ray attenuation (XRA)

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Introduction

The forestry policy in Europe is changing towards mixed forests, with a higher proportion of temperate hardwood (HW, abbreviations are summarised in Table 1) species, which are becoming more interesting from the climate change point of view (Kolling 2007). Exemplarily, the total share of HW in Germany increased between 2002 and 2014 by 7% and accounts for 43% of the total forestry area (BMEL 2015). European beech and oak have a share of 59.4% of the HW areas, but also ash, maple, lime, elm and many other species can be found in the mixed forests. The excellent mechanical HW properties (Kollmann and Côté 1968) are favourable for construction wood allowing for creating slenderer structural elements, reaching longer spans or for locally strengthening of softwood (SW) elements. Hitherto, oak, beech, chestnut, birch woods have the highest potential as structural elements (Aicher et al. 2014; Aicher and Stapf 2014; Frese and Blaß 2007; Jeitler et al. 2016). The HW glulam elements from ash and maple are also promising (Van de Kuilen and Torno 2014). In North America, maple glulam has a still unused high application potential (Manbeck et al. 1993; Janowiak et al. 1997). The key issues of HW glulam are the bonding and strength grading of the lamellas including the selection of an appropriate adhesive system and the durability of the composites (Aicher and Reinhardt 2007; Konnerth et al. 2016). Individualised bonding systems are necessary in view of the variability of HW species (Konnerth et al. 2016). The improvement of structural bonding of hardwoods is a hot spot research area (Schmidt et al. 2010, 2012; Knorz et al. 2014; Luedtke et al. 2015; Ammann et al. 2016).

Strength grading of HW lamellas will also be addressed in the present paper, dealing with the assignment into strength classes concerning strength, stiffness and density based on some visible or non-visible characteristics. The resulting parameters are required for modelling of glulam beams (Frese and Blaß 2007). The applied methodology is similar to that known from softwoods (SW) classification. Visual strength grading is a traditional approach relaying on the number and size of knots and the slope of grains. This cost-saving approach is also popular in HW sawing mills of small and medium size

Table 1: List of symbols and abbreviations.

Symbol, abbreviation	Definition
BAY	Bavaria, state in Germany
CDF	Cumulative distribution function
CV	Coefficient of variation
DENS	Density, mesured using XRA (kg m^{-3})
E	Edge knot, grading criterion after DIN 4074-5 (2008) (–)
$E_{0,mean}$	Modulus of elasticity parallel to the grain (MPa)
$E_{t,0,mean}$	Modulus of elasticity in tension (GPa)
f_t	Tensile strength parallel to the grain (MPa)
$f_{t,0,k}$	Tensile strength parallel to the grain, 5^{th} percentile value (MPa)
HW	Hardwoods
IP	Indicating property
IP DENS	Modelled density (kg m^{-3})
IP f_t	Modelled tensile strength (MPa)
IP_{KNOTS}	Machine measured knotiness parameter (–)
IP MOE	Modelled modulus of elasticity (GPa)
KC	Knot cluster, multiple knot criterion after DIN 4074-5 (2008) (–)
MC	Moisture content
MOE	Modulus of elasticity
MOE_{dyn}	Dynamic modulus of elasticity (GPa)
MOE_{static}	Static modulus of elasticity (GPa)
n	Number of specimens
$Q_{0.05}$	5^{th} percentile value
R^2	Coefficient of determination (–)
RH	Relative humidity
ρ	Density (kg m^{-3})
ρ_k	Density, 5^{th} percentile value (kg m^{-3})
SK	Single knot, important grading criterion after DIN 4074-5 (2008) (–)
SW	Softwood
TH	Thuringia, state in Germany
TS	Tensile strength
XRA	X-ray attenuation
μ	Mean value

companies. The prediction accuracy of the strength based on visual grading criteria results in R^2 values between 0.3 and 0.7 in the case of temperate HW species such as ash, beech, and oak (Oliver-Villanueva et al. 1996; Glos and Lederer 2000; Frühwald and Schickhofer 2005; Van de Kuilen and Torno 2014; Ehrhart et al. 2016a). For knot free HW specimens, the fibre deviation is an important criterion, but it is difficult to quantify. The fibre orientation on drying checks or the scribbling method on the wood surface are known approaches, but the reliability of booth methods is very limited (Glos and Lederer 2000; Frühwald and Schickhofer 2005). Machine grading is based on density or dynamic modulus of elasticity (MoE_{dyn}) measurement, for which experimental data from tensile/bending experiments are required. The machine grading of HW is less developed than that of SW, but MOE_{dyn} data for grading seems to be well suited for chestnut (Nocetti et al. 2010, 2016), oak (Kretschmann and Green 1999) and eucalyptus (Nocetti et al. 2017) with R^2 values between 0.33 and 0.44. MOE_{dyn} as a prediction variable is useful, also in case of SW/HW species combination (Ravenshorst 2015). The accuracy of approaches based on tension strength is considerably lower (Green and McDonald 1993; Frühwald and Schickhofer 2005; Van de Kuilen and Torno 2014).

For temperate HWs, the incorporation of visible grading criteria in the machine strength grading improves the strength prediction with R^2 values above 0.65 (Oliver-Villanueva et al. 1996; Frühwald and Schickhofer 2005). However, the accuracy is species specific and can be poor even for the multivariate models, which combine visual and machine parameters (R^2 of 0.33 for chestnut) (Vega et al. 2012). In the case of oak, beech and red maple, the machine measurements were combined with manual knottiness measurement for high quality lamella (Janowiak et al. 1997; Frese and Blaß 2007; Ehrhart et al. 2016b), which resulted in threshold values without compensating the values in a single regression model. The throughput rate of this approach is low.

In the case of SWs, automated grading machines are able to measure non-visible and visible grading criteria in one step, while multi-sensor systems generally combine knottiness, density and vibration measurement resulting in R^2 values of 0.69 (Bacher 2008). The common way to detect knottiness is the X-ray attenuation (XRA) measurement (Giudiceandrea 2005). This technique performs well for SW, as knots are twice as dense as the clear wood. For HWs, the difference between the knot and clear wood is low and leads to less accurate knot detection. The studies by Nocetti et al. (2010) on chestnut timber and Nocetti et al. (2017) on eucalyptus show only modest improvements in the case of machine measured knottiness and strength.

For European ash and maple no dedicated grading options are available with respect to glulam application, which is the main focus of this paper. The currently listed mechanical properties are derived from bending tests (Glos and Torno 2008). Therefore, the question arises which mechanical property values in tension can be obtained for visual grading, combined visual and machine grading, and fully automated machine grading? For the machine strength grading, a combined predictor of MOE_{dyn} and X-ray knottiness measurement will be considered. Mechanical properties and yields should be optimised for both species. Additionally, the mechanical properties will be compared to the property profiles needed for glulam production according to Kovryga et al. (2016b).

Materials and methods

To study the mechanical properties of ash (*Fraxinus* spp.) and maple (*Acer* spp.) boards, a total of 862 specimens were sampled from Central and Northern Germany (Table S1). The sample for ash included three sub-samples originating from northern Bavaria (BAY) and Thuringia (TH_I and TH_{II}), respectively. The BAY boards were cut from 200 to 600 mm diameter logs with a band saw, while the pith was discarded (Figure 1a). For HWs, a pith-free cutting pattern is preferred, as boards with pith tend to splitting and warping. The average quality of the logs corresponded to B/C (common/moderate quality) according to the roundwood standard EN 1316-1. The detailed description of the sawing pattern and log quality is provided by Van de Kuilen and Torno (2014).

The samples from TH were cut to 3 m boards from 200 to 390 mm diameter logs. For sample TH_{II}, the cutting pattern including pith (Figure 1b) was also considered to estimate the possibility of the entire wood utilisation. The quality of logs was on average C (moderate quality) and D (logs not assigned to classes A–C, whereby 40% of the log's volume is useable) according to the European roundwood standard EN 1316-1. For each of the ash and maple species, both TH_I and TH_{II}) were considered as a single sample, as the mean static MOE and 5th percentile of tensile strength (TS) differed for the subspecies by 5% and 6%, respectively. This difference lies within the natural variation for wood species (Stapel and Van de Kuilen 2014).

Visual strength grading: Visual strength grading in Europe is delegated to national grading standards. Here, the German visual grading rules DIN 4074-5:2008 (including ten visual criteria) for boards ("Brett/Bohle") were applied and the knottiness, presence of pith, bark inclusion, wane and fibre deviation were considered. Growth ring width is not included in the standard because it is not relevant for HW species (Oliver-Villanueva et al. 1996; Glos and Lederer 2000; Frühwald and Schickhofer 2005). The main knottiness parameters of the standard are: (1) Single knot (SK) or DIN Einzelast Brett (DEB) is defined as the ratio between the size of the largest knot related to the width of the board (Figure 2a). The size includes dimensions (width parallel to the edge) of an individual knot on all board surfaces. (2) Knot cluster (KC) or DIN Abstandsammlung Brett (DAB) is a multiple knot criterion, which considers all knots appearing in a moving window of 150 mm. Therefore, the spread of all knots over the 150 mm window is related to the width of the board (Figure 2b). The grading criteria SK and KC are relevant to the grading of boards and lamellas. The low knottiness values indicate small knot size and/or in the case of KC rare occurrence or the knots. (3) Edge knot criterion (E) or Schmalseitenast is an optional criterion for boards used for glulam production and represents the penetration depth of the knots appearing on the edge side only (Figure 2c). For several edge knots,

a

b

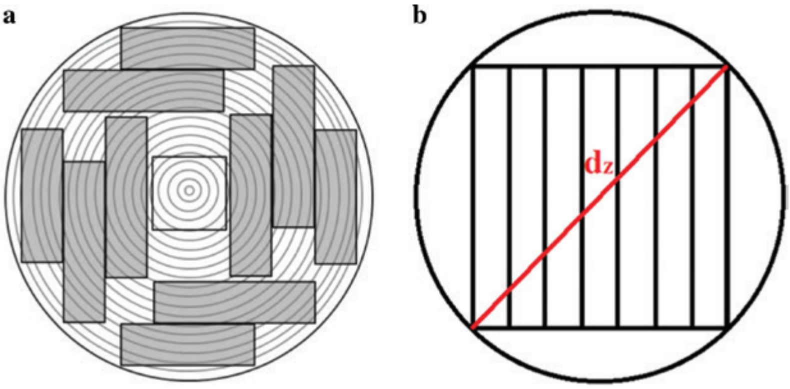

Figure 1: Sawing pattern chosen for the milling of (a) BAY sample (Torno et al. 2013) and (b) TH II sample. In (a) indicative "cutting all around" pattern and in (b) cutting pattern including pith are illustrated.

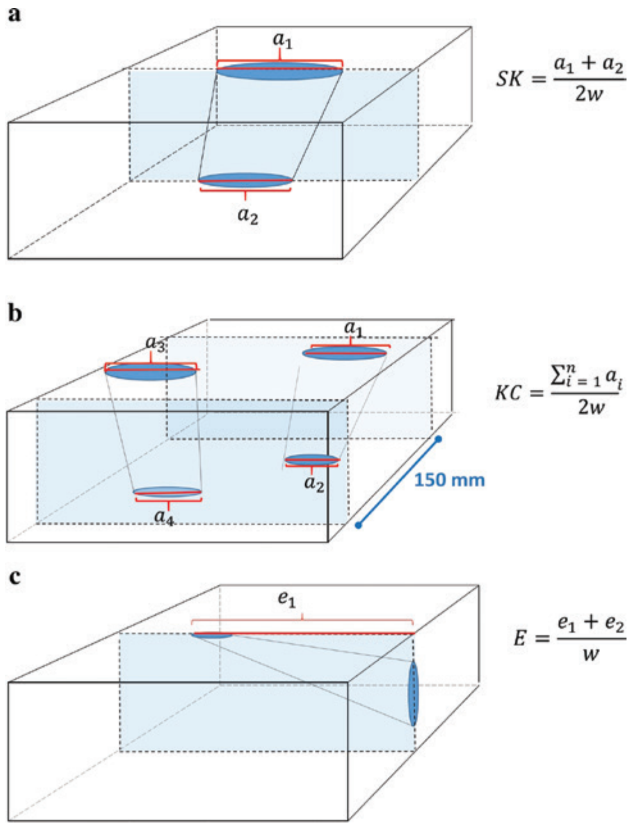

Figure 2: Measuring rules for knots according to grading rules for boards of German visual grading standard DIN 4074-1 and DIN 4074-5.
Figure illustrates different knotiness parameters: (a) SK, Single knot; (b) KC, knot cluster; and (c) E, edge knot.

the non-overlapping penetration within a 150 mm moving window is considered.

Fibre deviation is defined as an angle with the longitudinal axes of the sawn piece and is measured in % (grain angle). In this study, visible global fibre deviation was detected on drying checks and, additionally, the surface was assessed qualitatively for fibre deviations exceeding the limits of DIN 4074-5. Specimens exceeding the limits were graded as "reject". In addition, to quantify the fibre deviation and to estimate the possible effect on the grade determining properties, the numerical value of fibre deviation was estimated from the failure pattern after tension tests.

HW boards were assigned to visual grades LS13 (highest quality) to LS7 (lowest quality) based on the thresholds listed in Table 2. To assign a lamella to the visual grade, all boundary values had to be met, otherwise, the specimen was assigned to the next lower grade or rejected.

Machine strength grading: The MOE_{dyn} longitudinal to the grain was measured on laboratory equipment by means of a multi-sensor system. MOE_{dyn} combines the eigenfrequency measurement with density measurement (Eq. 1) and is dependent on the length of the board. The natural frequency from longitudinal oscillation was measured by an accelerometer as well as density. The R^2 between laboratory and in a multisensory-system is 99%.

$$MOE_{dyn} = 4f^2l^2\rho \quad (1)$$

Table 2: Threshold values for grading of hardwood lamellas according to DIN 4074-5:2008.

Grading property	LS13	LS10	LS7
Single knot (SK) (–)	0.2	0.333	0.5
Knot cluster (KC) (–)	0.333	0.5	0.666
Edge knot (E) (–)	–	–	–
Pith (–)	No	No	No
Fibre deviation (%)	7	12	16

Machine strength grading was performed on the MiCROTEC (Bressanone/Brixen, IT) GoldenEye 706 scanner. The multi-scanner system combines vibration measurement and X-ray scanning to obtain the MOE_{dyn}, density and knottiness (Bacher 2008; Giudiceandrea 2005). These parameters can be used either individually or in combination for property prediction. In the latter case, a mathematical model – the so-called indicating property (IP) model – was applied for a better prediction. To predict TS, individual non-linear regression models (Eq. 2) was created, in which the MOE_{dyn} and knottiness parameter from the X-ray scan (IP_{KNOTS}) are combined. IP_{KNOTS} is a ratio between the number of grid points classified as knots and the overall number of measurement points, both estimated in a 150 mm window frame. The model parameters were selected based on the finding, that both knottiness and MOE_{dyn} show significant ability for timber strength prediction. Visually measured knottiness shows the highest prediction accuracy for strength. Density was included into the model as the overall prediction accuracy increased by 0.03 (Nocetti et al. 2016). For the relationship between knottiness and TS, nonlinear relationship with power of b3 was selected, as the knottiness scatters exponentially to the TS (Figure 5).

$$IP\ ft = b_1 + b_2(IP_{KNOTS})^{b3} + b4MOE_{dyn} + b_5DENS \quad (2)$$

The model was fitted to the data by means of the Levenberg-Marquardt nonlinear least squares algorithm implemented in MATLAB Statistics and Machine Learning Toolbox ver. R2016a (Mathworks, Natick, MA, USA). Additionally, separate prediction models for the static modulus of elasticity and density were created:

$$IP\ MOE \sim MOE_{dyn} + IP_{KNOTS}; \quad (3)$$

$$IP\ DENS \sim DENS. \quad (4)$$

In this case, knottiness improved the prediction accuracy of MOE_{static} significantly by 0.05.

The three IPs served as benchmarks for the prediction of the grade determining properties (strength, stiffness and density). However, for the grading, two IPs [modelled tensile strength (IP ft) and modelled modulus of elasticity (IP MOE)] were considered. Modelled density (IP DENS) was not considered for the strength class assignment. The initial settings were derived separately for ash and maple to test the feasibility of machine grading. All mechanical property value requirements were met (FprEN 14081-2:2017) and were calculated in accordance with EN 14358:2016.

Compared to the procedure of FprEN 14081-2:2017, the verification steps have been skipped and less than four sub-samples were used for settings. Therefore, the settings are approximative to check the grading feasibility for selected species. It should be noted, that the settings are only representative for the growth area (Germany/Central Europe) of ash and maple, dimensions and sawing techniques used.

Particularly, the timber is sawn from small sized logs (TH) and small to medium-sized logs (BAY) of qualities suitable for sawn wood. However, for the final application in sawmills, the verification procedure is mandatory. The final yields and thresholds may therefore differ.

For the combined method (visual plus machine grading), MOE_{dyn} measured in Eq. 1 is combined with the visual assessment of boards with separate thresholds for each of the parameters and without allowing an interaction of the grading parameters in the regression model. This option was suggested by Frese and Blaß (2007) for beech glulam and is recommended in the German technical approval Z-9.1–679 (2013).

Destructive tests: The specimens were tested in tension in accordance with EN 408:2010 and EN 384:2016 with a testing span of 9 times the width. For all specimens, the grade-determining density, MOE and TS properties were measured under the conditions of 20°C/65% relative humidity (RH). Density was determined on clear wood specimens as specified by EN 408 (2010). Moisture content (MC) was measured in accordance with EN 13183–1:2002 and was on an average 11% for each of the species and sub-samples. The MOE and density were adjusted to the reference MC of 12% and the TS adjusted to 150 mm width based on the equations listed in EN 384:2016. The characteristic values were calculated in accordance with EN 14358:2016 non-parametric method.

Optimisation of grading thresholds: Setting grading thresholds for both visual and combined grading is a required step to produce sawn timber with the desired mechanical properties with simultaneous yield maximising. Both higher yield and enhanced mechanical properties are the desired objectives, but these requirements are conflicting, as a higher yield can be obtained only by reducing the mechanical properties *ceteris paribus*. Therefore, a multi-objective optimisation was applied:

$$\max F(x) = [f_{yield}(x), f_{class}(x)], \tag{5}$$

where f_{yield} and $f_{strength}$ are the objective functions and $x = (x_1, x_2 \ldots, x_N)^T$ is the vector of the decision variable, i.e. in our case the grading thresholds. The objective functions calculate the yield and strength class assignment for each combination of grading thresholds.

For problem solutions, the multi-objective optimisation based on evolutionary algorithms, particularly the genetic algorithm NSGA-II presented by Deb et al. (2002), was applied. The underlying principle for all evolutionary algorithms is similar, i.e. the extinction of weak and unfit species by natural selection (Konak et al. 2006). Fitter and stronger individuals have a greater chance of passing to the next generation. The application of this algorithm to grading is explained in detail by Kovryga et al. (2016a). Boundary values are optimised for each successive grading class LS13 to LS7, beginning with the highest class. This gives the highest yield and highest strength class for the highest grades.

TS classes: No TS classes are currently listed for HWs in the European strength class systems. The highest TS class for SWs is T30 (characteristic TS 30 MPa). To study the potential of HW species, the material profiles derived by Kovryga et al. (2016b) were used as a basis. Table 3 shows the material profiles named DT (deciduous TS) classes. As TS classes for HWs begins with the characteristic TS of 18 MPa for the lower valued specimens. In the current study, SW strength classes will also serve for the classification.

Table 3: Selection of TS-classes for softwoods (T-classes, adopted from EN 338 (2016) and proposed TS-classes for hardwoods (DT-classes), adopted from Kovryga et al. (2016b).

	Properties		
Classes	**$f_{t,0,k}$ (MPa)**	**$E_{0,mean}$ (GPa)**	**ρ_k (kg m^{-3})**
T-classes for SW			
T14	14	11	350
T14.5	14.5	11	350
T15	15	11.5	360
T16	16	11.5	370
Proposed DT-classes			
DT18	18	12	550
DT22	22	13	550
DT25	25	13.5	550
DT28	28	14	550
DT30	30	14.5	550
DT34	34	15	610
DT38	38	15.5	610
DT42	42	16	620
DT46	46	16.5	630
DT50	50	16.5	640
DT54	54	17	640

Results and discussion

Ungraded properties

Table 4 shows the values for the visible and mechanical properties of ungraded ash and maple boards. For ash, the mechanical properties differ between TH and BAY. The boards from BAY sample show lower TS, MOE_{static} and densities compared to the TH sample. The higher values for ash boards are comparable to those for ash boards presented by Frühwald and Schickhofer (2005) as well as for both 5th percentile and mean. Van de Kuilen and Torno (2014) reported higher values, though specimens were tested with reduced testing length.

The ratio between mean density and characteristic density differs between northern Germany and Central Germany growth regions, with the ratio of 1.2, which is specified in EN 384 for SWs and HWs. The coefficient of variation is low for density, particularly in Central Germany. The variation of TS is very high for all specimens and samples (CV > 0.470).

The European maple values are comparable to those of red maple reported by Green and McDonald (1993), who reported mean TS values as high as 62.8 MPa for visually graded timber following standard grading rules (NELMA 1991) based on "select structural" (SS), and 41.3 MPa for grade No. 3, and mean MOE values of 13.0 GPa and

Table 4: Descriptive statistics of visual and mechanical properties of ash (*Fraxinus* spp.) and maple (*Acer* spp.) boards.

		Ash		
Parameter	**Statistics**	**BAY**	**TH**	**Maple TH**
n		178	303	381
SK (–)	μ	0.07	0.079	0.115
	CV [–]	1.450	1.135	0.992
KC (–)	μ	0.09	0.102	0.149
	CV [–]	1.525	1.159	1.002
MOE_{dyn} (GPa)	μ	13.7	16.2	14.5
	CV [–]	0.164	0.111	0.118
ρ (kg m^{-3})	μ	657	701	664
	CV [–]	0.097	0.067	0.067
	$Q_{0.05}$	549	635	569
MOE_{static} (GPa)	μ	12.7	15.6	13.8
	CV [–]	0.206	0.146	0.16
f_t (MPa)	μ	52.7	67.1	53.4
	CV [–]	0.470	0.487	0.490
	$Q_{0.05}$	19.4	23.0	18.9

BAY, Bavaria; TH, Thuringia.

11.85 GPa, respectively. The results, however, should be compared with caution due to a possible size effect, as the specimens were tested in tension with a free test duration of 16 h in the study of Green and McDonald (1993) and only 9 h in the present study. Maple shows lower tensile and bending properties than ash (Glos and Torno 2008).

Strength grading parameters

Table S2 shows the type and number of different wood features, with the exception of knots. Overall, a high proportion of boards with pith was observed. The BAY sample contains fewer pith boards compared to TH samples as in the former the larger log dimensions, combined with a special pith-omitting sawing pattern reduced the relative moiety of the pith. Nevertheless, some stocks of pith boards are present due to stem eccentricity. For some boards, the presence of pith coincides with fibre deviation, thus pith removal also means mitigating fibre deviation.

The cumulative distribution function of TS for ash and maple boards is shown in Figure 3, where visually observable fibre deviation reveals TS values in the lower part of the strength distribution. Specimens showing a visible fibre deviation should be rejected, though the fiber deviation is difficult to quantify (Frühwald and Schickhofer 2005). Rejecting these specimens affects the bottom part of the distribution (Figure 3), and it is a criterion applied by Ehrhart et al. (2016b) for grading of beech boards into classes with TS values of 50 MPa.

The pith-containing specimens in lamellas (154 for ash and 137 for maple) show a higher frequency of low-strength values compared to the cumulative frequency distribution of the whole dataset. The mean strength values for the pith-containing boards are of 49.7 and 44.9 MPa for ash and maple, respectively, lower than pith-free boards, with 67.2 and 58.4 MPa, respectively. This supports the findings by Glos and Lederer (2000) and Frühwald and Schickhofer (2005) concerning the strength-reducing effect of pith. Nevertheless, strength values of pith-containing specimens range up to 130 MPa, with a considerable fraction of test values above 40 MPa (over 50% for ash and 40% for maple). Rejecting pith during visual assessment oversimplifies the relationship and leads to lower yields and not necessarily higher strength values. Moreover, other criteria

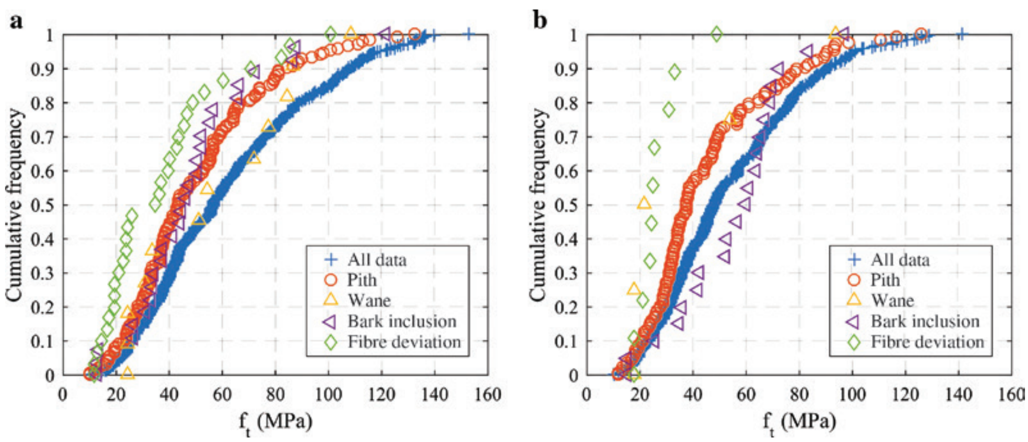

Figure 3: Empirical CDF of tensile strength grouped by defect type for ash (a) and maple (b). For each defect the distribution of tensile strength values is illustrated.

Figure 4: Maple specimen, failure at the slope of grain.

in pith-containing boards, such as knottiness or fibre deviation, also impact strength. For some boards, as can be seen in Table S2, several wood features are significantly overlapping. Figure 4 shows an example of a pith board with failure induced by the grain slope.

There are indicators that pith boards do not affect the properties of glulam, as shown by Janowiak et al. (1997), who found that the quality of the inner and outer log materials are very similar. On the other hand, pith boards tend to have a higher number of splits (Glos and Lederer 2000) and the glulam TS perpendicular to the grain ($TS_{\perp}$) is also deteriorated in presence of pith. The study by Hübner (2013) revealed that ash glulam $TS_{\perp}$ differs significantly between boards without and with pith.

Table 5 shows the relationship between grading parameters and TS. Generally, knottiness shows the highest correlation to strength as a single parameter. R^2 values over 0.37 for ash and 0.475 for maple are far beyond those obtained for SWs, that range from 0.15 to 0.35 (Denzler et al. 2015). Knot free and boards with small knots are analysed together as will be the case under practical production conditions. Assuming non-linear conditions, even higher R^2 values between knot cluster and strength (0.466 for ash and 0.588 for maple) can be obtained (Figure 5). In contrast, the impact of the edge knot criterion is low with an R^2 of 0.051, because this criterion is valid only on the edge and not under single

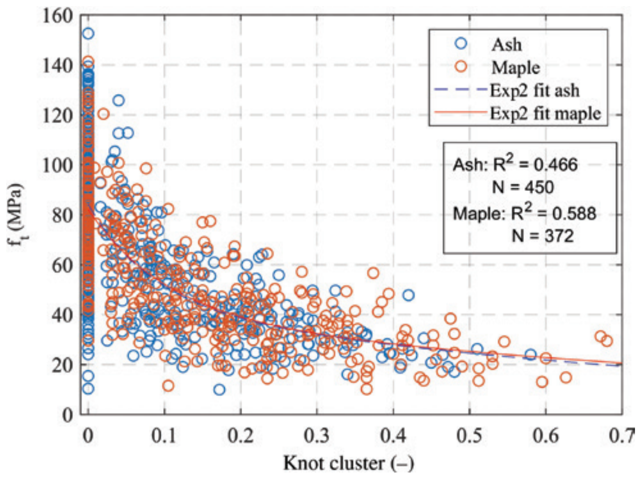

Figure 5: Scatter plot between knot cluster and tensile strength for ash and maple with an exponential fit.
Visible fibre deviation and large bark inclusions are rejected.

Table 5: Coefficient of determination (R^2) for the prediction of grade-determining properties for ash and maple.

	Ash			Maple		
Grading parameters	ρ_{12}	E_0	$f_{t,150}$	ρ_{12}	E_0	$f_{t,150}$
Visual grading						
SK (all data)	0.013	0.121	0.381	0.098	0.237	0.475
SK (w/o knot free spec.)	0.000	0.217	0.334	0.068	0.222	0.403
KC (all data)	0.007	0.119	0.377	0.087	0.208	0.461
KC (w/o knot free spec.)	0.000	0.206	0.345	0.056	0.182	0.385
E	0.008	0.000	0.051	0.022	0.040	0.098
Pith	0.017	0.001	0.071	0.015	0.025	0.059
Fibre deviation (after break)	0.001	0.011	0.025	0.012	0.016	0.028
Fibre dev. (after break, knot free)	0.005	0.002	0.072	0.10	0.009	0.023
Machine grading						
MOE_{dyn}	0.519	0.737	0.270	0.013	0.184	0.288
IP_{KNOTS}	0.008	0.109	0.197	0.188	0.590	0.143
IP MOR (logstrength)	0.113	0.603	0.484	0.024	0.441	0.485
IP MOR_nlinear	0.098	0.516	0.576	0.018	0.397	0.533
IP MOE	0.519	0.786	0.315	0.114	0.641	0.251
IP DENS	0.907	0.351	0.039	0.896	0.025	0.032

knot and knot cluster conditions. Despite the high correlation of knottiness parameters to TS, a high TS variation for knot-free and low-knottiness specimens (KC < 0.1) is visible (Figure 5). The TS ranges from 10 to 150 MPa and increases the importance of other criteria in addition to knottiness, which does not provide satisfactory strength prediction for high quality material. As shown in Figure 3, pith and larger fibre deviation affects the average quality and the TS values are decreasing in most cases.

The machine grading parameters show medium to high prediction accuracy for both TS and stiffness. Non-linear grading model improves the strength prediction (Figure 6), i.e. R^2 is 0.576 for ash and 0.533 for maple. In this case, machine knottiness does not improve the data based on MOE_{dyn} alone (R^2 for ash 0.276 and 0.151 for maple), as MOE_{dyn} is estimated over the entire length of the timber piece and lowers the effects the size and position of local defects. The prediction strength of the combined models is lower compared to similar SW models, where R^2 values of up to 0.69 are usual (Bacher 2008). The low R^2 values are due to the lower correlation between knottiness and strength of HWs because the algorithm is not optimised for HWs, where the similar densities of clear HW and knots has to be considered (Giudiceandrea 2005).

For both species, density and stiffness are best predicted by the IP DENS and IP MOE, respectively. The measured R^2 values between IP MOE and TS are comparable to those reported by Frühwald and Schickhofer (2005) for temperate European HWs and by Green and McDonald (1993) for red maple. Neither IP MOR nor IP MOE provides accurate measurement for density (R^2 below 0.1), even though density is part of the strength prediction model and included in MOE_{dyn} calculations. This behaviour is related to the low correlation between TS and density, which is even negative for maple ($r = -0.180$), meaning a density decrement for higher strength values. This pattern can be attributed to species-specific characteristics, as density decreases with age for Norway maple and sycamore maple (von Wedel 1966). Outer parts display higher quality in terms of lower knottiness, while at the same time lower density values are measured.

Visual grading

The optimised thresholds for grading after DIN 4074-5 are presented including the optional knot criteria.

Table S3 shows the grading results according to German visual grading rules. Concerning the yields, the highest grade LS13 accounts for over 50% of the ash and maple lamellas. Rejects constitute the 2nd highest category. Differences between ash sub-samples are observable. Over 80% of boards from BAY were assigned to the LS13 grade, whereas lamellas from BAY showed only 10.5% rejects, and 40.9% of the lamellas from TH were rejected. The latter is due to a high number of pith containing boards that are generally rejected for HWs by DIN 4074-5 (2008). The pith boards are the result of different sawing patterns chosen. This supports the findings by Glos and Torno (2008) that the quality of HW timber is either high or at a low quality level, and no specimens belongs to medium grades.

In the compilation of Table S4, the properties of LS13 ash differ between sub-samples. Lamellas from BAY have the lowest strength values with 23.8 MPa and MOE values with 12.8 GPa, whereas lamellas from TH dispose of data

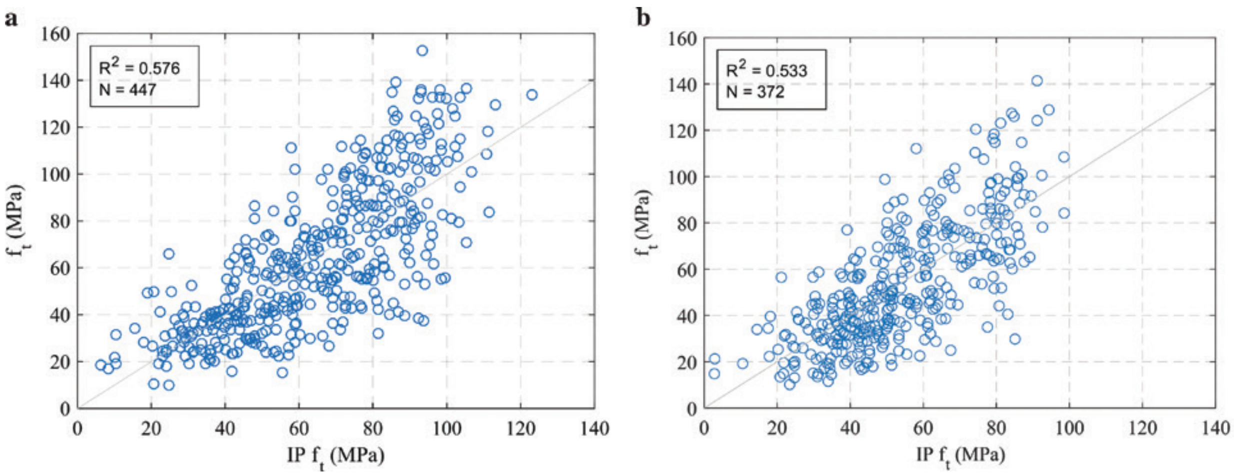

Figure 6: Scatter plot of the relationship between predicted tensile strength IP ft and measured tensile strength of ash (a) and maple (b), graphs are used in conjunction with EN 14081-2 and EN 14358 for the determination of grade thresholds.

around 36 MPa. The strength values for maple assigned to LS13 are with 34 MPa slightly lower than that of ash. The mean MOE for maple is with 14.5 GPa, not as high as the one for ash from TH. If the samples are assigned to the strength class profiles proposed by Kovryga et al. (2016b), the ash data exceed the requirements of DT34 for the TH and BAY samples only in case of assignment to DT22. The difference is due to the specimen's origin and partly due to size effects, as the BAY sample specimens include both large and small cross-sections. Large cross-sections show lower strength values. No adjustment for specimens with height over 150 mm to the reference height of 150 mm is required according to EN 384:2016. For the assignment of LS13, the TS was the grade-limiting property.

Applying the "edge knot criterion" to lamella grading is optional. If a criterion is applied, the yield for the highest grade is reduced only slightly compared to the lamella rules presented above. A maximum of 3.0% for the TH sample and minimum of 0.6% for the BAY sample was seen. There is also an effect on TS, which increases slightly by 0.6 MPa for both species. In Figure 7, the scatter plot between edge knot criterion and the TS for timber graded is presented. A high variation in TS for edge knot-free (E = 0) timber can be observed. Lamellas containing edge knots show homogenous scatter in TS for increasing edge-knot penetration depth. Thus, TS does not seem to be affected by edge knot size. The low R^2 values of 0.05 and 0.098 between edge knot and TS for ash and maple, respectively, supports this conclusion. Stapel and Van de Kuilen (2014) showed the limited significance of the edge knot criterion for tension loaded spruce boards. The edge knot criterion, however, is mandatory if boards are used for flatwise bending applications.

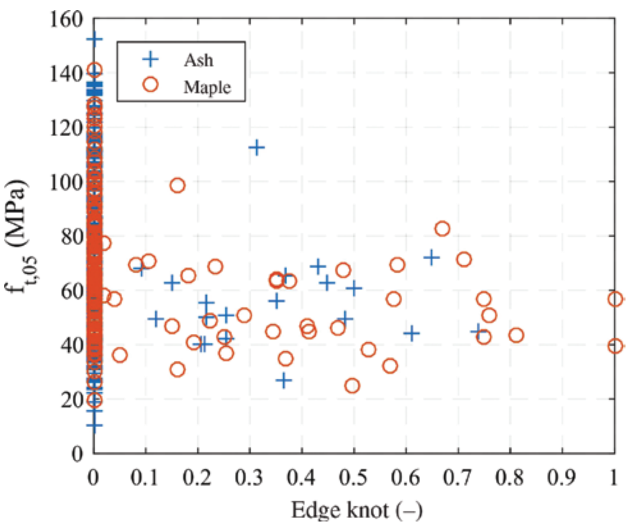

Figure 7: Scatter plot of the relationship between the edge knot criterion as per DIN 4074-5 and tensile strength for specimens assigned to LS13 of DIN4074-5 (2008), without considering the edge knot criterion.

The grading boundaries were optimised aimed at increasing the mechanical properties and yields and also for selection of easily applicable parameters (Table 6). Solution A represents grading to the highest possible strength class (DT34 in this case), while solution B is used to benchmark the visual grading. Grading to DT34 allows for higher mechanical properties at the expense of lower yields. In this case, density requirements are not considered. If graded to DT30, 10% higher yields can be achieved compared to visual grading. With the selected precision of optimisation steps (0.1), grading to DT28 was not possible. Smaller changes in the knottiness boundary values would make grading less robust because the actual knot measurement is vulnerable to the human estimates error. Regarding the grading thresholds, one should keep in mind that thresholds of 0 are a numerical value, as knots below 5 mm are not considered.

For maple, visual grading to DT30 is possible. Compared to visual grading as per DIN 4074-5 (2008), no higher strength class assignment is possible. Solution A represents grading to the same grade as visual strength grading: In this case, the yield is 5% higher and the remaining timber can be utilised as T14. A possible application for the low-grade lamellas would be the inner part of glulam beams. Solution B represents grading to a lower strength class (DT28). In this case, 22.8% higher yields are possible.

The grading results show the high potential of visually graded ash and maple lamellas for glulam production, especially compared to SW lamellas. Machine-graded spruce can be assigned to T30 ($f_{t,0,k}$ = 30 MPa and $E_{0,mean}$ = 15.5 GPa). Based on the result by Stapel and Van de Kuilen (2014), visually graded spruce can be assigned to T22. Yields of only 20% are likely. The high yield of HWs at the highest grade levels are attractive. However, from the economic feasibility point of view, the yield from log to lamellas is a more accurate indicator. For HWs, higher volumetric losses occur during processing (e.g. due to sawing and shrinkage losses).

Combined visual and machine strength grading

Combined visual and machine grading improves the results. The edge knot criterion was not included in the optimisation procedure due to the marginal effect on TS. Optimisation with an edge knot allowed only for slightly

Table 6: Optimised visual grading threshold values and mechanical properties for ash and maple.

Wood, solution	Grade	Threshold values			Characteristic values			Tensile class	Yield (%)
		SK (–)	KC (–)	Pith	ρ_k (kg m^{-3})	$E_{0,mean}$ (GPa)	$f_{t,0,k}$ (MPa)		
Ash									
DIN	LS13	0.2	0.333	No	559	14.9	28.7	DT28	61.3
	LS10[a]	0.333	0.5	No	625	12.3	17.6	T16	7.1
	LS7[a]	0.5	0.666	No	596	10.2	15.3	T13	1.1
	Rej								30.4
A	LS13	0	0	Yes	549[b]	15.0	36.8	DT34	43.8
	LS10	0.1	0.3	yes	596	15.0	27.9	DT25	27.6
	LS7	0.4	0.6	Yes	609	13.5	18.1	DT18	28.4
	Rej								0.2
B	LS13	0.1	0.3	Yes	570	15.1	30.7	DT30	71.3
	LS10	0.4	0.6	Yes	610	13.4	18	DT18	28.4
	Rej								0.2
Maple									
DIN	LS13	0.2	0.333	No	546[b]	14.5	34	DT30	50.3
	LS10[a]	0.333	0.5	No	616	12.6	14.9	T14	9.7
	LS7	0.5	0.666	No	620	11.0	11.9	-	3.8
	Rej				588	13.2	16	-	36.3
A	LS13	0.1	0.3	Yes	546[b]	14.6	32.1	DT30	55.4
	LS10	0.6	0.8	Yes	611	12.6	14	T14	44.6
	Rej								0.0
B	LS13	0.2	0.3	Yes	555	14.3	28.4	DT28	73.1
	LS10	0.4	0.5	Yes	614	12.4	15.1	T15	22.6
	Rej								0.2

[a]n < 40. Characteristic properties calculated using parametric method of EN 14358 (2016). [b]Characteristic density does not match the requirements of the strength class.

higher yields in the higher classes. Thresholds for assigning ash lamellas to the characteristic TS of 62 MPa are possible, though yields are low (11%). Combinations with yields above 20% are more beneficial as enough volume for production is available. Compared to ash, maple with a TS of up to 42 MPa is possible. Table 7 shows the selected optimal boundary combinations. For ash, combination A (solution “A”) gives an economically attractive yield (23%) and good properties (DT54). Solution “B” shows the thresholds for assigning the highest grade to DT38. This currently appears to be the most efficient solution. As for ash, in combination with the best available gluing systems, a characteristic finger-joint tension strength of up to 35.1 MPa can be achieved (Van de Kuilen and Torno 2014). Over 56.4% of the specimens is suitable for the highest grade. Solution “C” is a benchmark performance of visual grading in terms of yield. In this case, higher yields (74.9%) can be achieved than in case of visual grading (61.3%). The yields are slightly higher than the ones based on optimised visual grading (71.3%). The characteristic property values match the TS class profiles for HWs.

The mechanical properties of maple are inferior to those of ash. The highest possible strength class assignment is DT42 grading (Table 7, solution A). For all strength classes, the characteristic properties fit the required values, with the exception of density, and all values should be elevated for a higher strength class assignment. Grading to DT38 allows assigning to the 2nd lowest grade to DT25, with yields almost equally distributed between the grades.

The coefficient of variation (CV) for combined grading is lower than for visual grading, falling in the case of the TS of DT54 ash below 0.27 and 0.09–0.1 for the characteristic MOE_{static}. For maple, the CV of MOE_{static} is even lower (0.08–0.09). For both species, the lowest class can be assigned to grades T15/T16 and DT18, respectively. The obtained properties of lower grade samples are comparable to those of red maple glulam inner laminations (Janowiak et al. 1997).

The optimised thresholds for grading by the combined approach tolerates the presence of pith. All parameter combinations are successful with the exception for grading to DT54 (solution “A”) for ash. For achieving TS values below 54 MPa, the pith criterion seems to be less important. The observation for the pith criterion on the CDF of TS in section “Strength grading parameters” reinforces this conclusion. A separate analysis for the effect of pith on the properties of glulam is required. Density

Table 7: Grading thresholds and mechanical properties for combined visual and machine strength grading of ash and maple boards.

Species, solution	Grade	Threshold values SK (–)	KC (–)	E (–)	Pith	E_{dyn} (GPa)	Characteristic values ρ_k (kg m^{-3})	$E_{0,mean}$ (GPa)	$f_{t,0,k}$ (MPa)	Tensile Class	Yield (%)
Ash											
A	1	0	0	–	No	15.7	641	17.1	57.5	DT54	23.1
	2	0.1	0.1	–	Yes	13.4	624	15.9	34.4	DT34	32.9
	3	0.5	0.6	–	Yes	–	545[a]	12.7	18.2	DT18	44.0
	Rej										0.0
B	1	0.1	0.1	–	Yes	13.1	629	16.0	38.4	DT38	56.4
	2	0.5	0.6	–	Yes	–	545[a]	12.8	18.2	DT18	43.6
	Rej										0.0
C	1	0.2	0.4	–	Yes	13.1	624	15.5	30.2	DT30	74.9
	2	0.4	0.6	–	Yes	8.3	525	11.5	16.3	T16	24.4
	Rej										0.2
Maple											
A	1	0.1	0.1	–	Yes	15.0	617	16.0	42.1	DT42	24.2
	2	0.2	0.2	–	Yes	13.0	605	14.0	28	DT28	34.7
	3	0.3	0.6	–	Yes	–	532	12.5	16.3	T16	32.8
	Rej										8.3
B	1	0.1	0.1	–	Yes	13.9	613[a]	15.5	41.3	DT38	37.1
	2	0.2	0.5	–	Yes	12.2	601	13.5	25.2	DT25	33.6
	3	0.3	0.6	–	Yes	10.9	539	12.4	15.2	T15	18.5
	Rej										8.1
C	1	0.2	0.3	–	Yes	12.0	608	14.6	30.2	DT30	62.9
	2	0.4	0.5	–	Yes	–	527	12.3	15.8	T15	32.8
	Rej										4.3

[a]Characteristic density does not match the requirements of the strength class.

requirements were not considered strictly, as the values deviated from the ones specified in the profiles by less than 5 kg m^{-3}. Assigning the specimens to lower grades based on density appears to be inefficient.

Machine strength grading

Three combinations for (a) grading to the highest strength class, (b) grading to the maximum possible finger-joint strength, and (c) grading to the highest possible visual grade are presented below. Table 8 shows the properties and yields for grading to the selected class combinations. For ash, grading to DT54-DT34-DT18 shows only low yields for the highest grade DT54 (9.2%) and higher yields to DT34 and DT18. Machine grading to DT50-DT34-DT18 appears more reasonable, as yields of approximately 15.7% and a characteristic strength of 51.8 MPa can be obtained. The DT38-DT18 combination also shows promising results. For finger-joints, strength of 35 MPa (Van de Kuilen and Torno 2014) and yields around 55% can be obtained in the grade DT38. For grading to DT30, yields up to 71.8% are possible. The characteristic property values match the profiles. Nevertheless, the characteristic density does not match the property profiles (Table 3) in each case. For maple, the highest possible strength class achieved is DT42 (DT42-DT28-DT18) with yields up to 10 %. For grade DT38 – with TS data corresponding to the maximum finger-joint TS – a higher yield of 38% can be achieved (lower than for ash). Grading to DT30 allows for yields slightly above 50%. Machine grading, allows only low yields around 10% at the highest grade levels (ash graded to DT 54 and maple graded to DT42). The low yields are caused by the high variation in strength for the higher IP values (higher variation of residuals). In this case, characteristic strength calculated according to EN14358:2016 is decreased by the calculation procedure because of the high variation. Obviously, machine grading is better than the visual one, which also allows for grading to higher classes. Strength values above 28 MPa is substantial for machine-graded HW lamellas, especially when compared to visual strength grading. Thus, for ash machine-graded to DT30, the yields are 10.5% higher than that of ash lamellas visually graded to S13 (DT30). For maple, machine grading yields are 6.3% higher.

For the highest grades, DT54 for ash and DT42 for maple, the yields for machine grading are twice as low

Table 8: Grading IP thresholds and mechanical properties of ash and maple boards graded using non-linear IP ft model.

Grading class comb.	Strength class	n	Thresholds: IP f_t MPa	Thresholds: IP MOE (GPa)	Characteristic values: ρ_k (kg m^{-3})	Characteristic values: $E_{0,mean}$ (GPa)	Characteristic values: $f_{t,0,k}$ (MPa)	Yield (%)
Ash								
DT54-DT34-DT18-Rej	DT54	41	94.3	16.4	645	18.1	54.6	9.2
	DT34	226	54.5	9.8	607[a]	15.5	34.1	50.6
	DT18	180	6.4	7.4	545[a]	12.7	18.1	40.3
								0
DT50-DT34-DT18-Rej	DT50	70	88.6	15.9	643	17.7	51.8	15.7
	DT34	196	57.3	10.1	568[a]	15.1	34.4	43.8
	DT18	181	6.4	7.4	568	12.9	18	40.5
								0
DT38-DT18-Rej	DT38	246	58.8	10.1	620	16.1	38.3	55.0
	DT18	201	6.4	7.4	546[a]	12.9	18.1	45.0
								0
DT30-T16-Rej	DT30	321	47.4	8.9	575	15.6	30.1	71.4
	T16	126	6.4	7.4	565	12.2	17.7	28.6
								0
Maple								
DT42-DT28-DT18	DT42	39	64.7	15.4	609[a]	16.5	43.6	10.5
	DT28	192	46.2	8.7	554	14.2	28.1	51.6
	DT18	97	32	7.7	591	12.6	16.1	26.1
								11.8
DT38-DT25-DT15-Rej	DT38	110	63.7	11.7	605[a]	15.5	38.3	29.3
	DT25	119	46.2	9.3	602	14.1	25	30.9
	T15	128	23.7	6.4	532	12.4	15.5	34.4
								5.4
DT30-DT16-Rej	DT30	210	49.5	8.7	560	14.7	30.1	56.5
	T16	140	25.1	6.4	573	12.7	16.1	37.6
								5.9

[a]Characteristic density does not match the requirements of the strength class.

(over 10% differences) than the ones using a combined grading approach. For lower grades, however, such as DT38 for ash, machine-graded yields are at 55%, only slightly lower than the combined yields graded to DT38 (56.4%). For maple graded to DT38, the difference is slightly larger. Machine grading leads to 7.4% lower yields than the combined grading approach.

The high yields to DT54 for ash and DT42 for maple is attractive for producing premium products with high mechanical properties. In the case of machine-grading, higher throughput rates are possible, though it is not as attractive as in case of the combined grading approach. Improvements in machine strength grading prediction discussed earlier would increase efficiency of grading machines. To utilise material properties efficiently, a reliable finger-joint connection is required. Machine grading to class combinations containing DT34 and/or DT38 appears interesting. The yield for the strength class is only a few percent lower compared to the combined grading approach. In this case, higher processing speed and, thus, higher production volume is likely to compensate for the lower grading yields.

Strength class profiles

Figures S1 and S2 summarise all property data for the class combinations and grading methods compared to the TS profiles for HWs according to Kovryga et al. (2016b) and the profiles for SW (T-classes) as per EN 338:2016. Generally, for high-quality lamellas with strength >28 MPa, the properties for visual and machine grading methods match the profiles. Though for ash the MOE appears to be undervalued, the scatter of MOE values for the same strength grade reaches the profiles. Thus, for DT34, the MOE ranges between 15 and 16 GPa.

For samples assigned to grades below DT22, the empirically estimated MOE exceeds the values of the proposed DT-classes. Therefore, by assigning the samples to DT classes with lower MOE values, the actual MOE is undervalued. Due to the low correlation between knottiness and MOE, visual grading does not permit sufficient distinction between MOE values.

For machine-graded timber, the characteristic MOE values exceed the profiles (Table 3) due to the grading procedure itself and to the assumptions made for the strength profile definitions (Kovryga et al. 2016b). For machine grading, in addition to the IP f_t a separate IP for stiffness is used, allowing a higher stiffness prediction compared to grading based on a single IP or to visual grading. Moreover, the HW profiles for TS > 30 MPa are based on the model of visually determined knottiness and MOE_{dyn} that show higher strength prediction accuracy ($R^2 = 0.56$) and lower stiffness prediction accuracy ($R^2 = 0.59$) compared to the data presented here (Table 5).

Conclusions

Visual grading in accordance with German visual grading standard DIN 4074-5 (2008) allows for high tensile properties for the highest grades resulting in TS of up to 30 MPa, which is achieved for machine graded SW timber as a maximum. Higher mechanical properties can be achieved via combined visual and machine strength grading, as well as via fully automated grading. If grading HW timber by the combined approach for ash, a characteristic TS of 62 MPa is possible, and 42 MPa for maple. Automated grading systems based on combination of MOE and X-ray knot detection allows increasing the prediction accuracy to 0.576 for ash and to 0.533 for maple compared to the MOE_{dyn} strength prediction. Compared to the combined grading, lower yields are achieved via grading to classes with superior characteristic property values (>50 MPa for ash). The graded lamellas show good agreement with the material profiles proposed by Kovryga et al. (2016b). These profiles reflect MOE_{static} values better than the profiles of SW-T-classes for the highest grades obtained by visually grading or by combined grading of boards. However, for visually graded timber to lower grades (e.g. LS10) and machine-graded timber, the actual MOE_{static} values are underestimated. The "pith" parameter has little impact on TS properties parallel to the grain during grading. Rejecting the pith allowed only for grading to higher strength classes resulting in strength >54 MPa. For classes with lower property values, the pith may be present in the boards leading to higher yields. Pith is not detrimental in boards applied for glulam beams, if the desired mechanical properties of the final glulam product remain unaffected. The use of the edge knot criterion does not affect the TS properties of the boards in a meaningful way and as such, it can be excluded for grading of tensile loaded boards.

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References

Aicher, S., Reinhardt, H.-W. (2007) Delaminierungseigenschaften und Scherfestigkeiten von verklebten rotkernigen Buchenholzlamellen [Delamination properties and shear strength of glued beech wood laminations with red heartwood]. Eur. J. Wood Prod. 65:125–136.

Aicher, S., Stapf, G. (2014) Glulam from European white oak: finger joint influence on bending size effect. In: Materials and Joints in Timber Structures. Recent Developments of Technology; RILEM Book series, Vol. 9. Eds. Aicher, S., Reinhardt, H.-W., Garrecht, H. Springer, Dordrecht, The Netherlands. pp. 641–656.

Aicher, S., Christian, Z., Dill-Langer, G. (2014) Hardwood Glulams – Emerging Timber Products of Superior Mechanical Properties. In: Proceeding of WCTE 2014, Quebec City, Canada. August 10–14.

Ammann, S., Schlegel, S., Beyer, M., Aehlig, K., Lehmann, M., Jung, H., Niemz, P. (2016) Quality assessment of glued ash wood for construction engineering. Eur. J. Wood Prod. 74:67–74.

Bacher, M. (2008) Comparison of different machine strength grading principles. In: Proceedings of Conference COST E53, 29–30 October, Delft, The Netherlands.

Bundesministerium für Ernährung und Landwirtschaft (BMEL). (2015) Der Wald in Deutschland – Ausgewählte Ergebnisse der dritten Bundeswaldinventur [The Forests in Germany – Selected Results of the Third National Forest Inventory]. BMEL, Bonn, Germany.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T. (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evolut. Computat. 6:182–197.

Denzler, J., Diebold, R., Glos, P. (2015) Machine strength grading – commercially used grading machines – current developments. In: Proceedings of the 14th International Symposium on Nondestructive Testing of Wood, Hannover, Germany. pp. 9–16.

DIN 4074-5. (2008) Strength grading of wood – Part 5: Sawn hardwood. DIN, Berlin.

Ehrhart, T., Fink, G., Steiger, R., Frangi, A. (2016a) Experimental investigation of tensile strength and stiffness indicators regarding European beech timber. In: Proceeding of WCTE 2016, Vienna, Austria. August 23–25. TU Verlag, Vienna.
Ehrhart, T., Fink, G., Steiger, R., Frangi, A. (2016b) Strength grading of European beech lamellas for the production of GLT and CLT. In: Proceedings of 49th INTER and CIB Meeting, Graz, Austria.
EN 13183-1. (2002) Moisture contentof a piece of sawn timber – Part 1: Determination by oven dry method. CEN European Committee for Standardization, Brussels.
EN 408. (2010) Timber structures – structural timber and glued laminated timber – determination of some physical and mechanical properties. CEN European Committee for Standardization, Brussels.
EN 14358. (2016) Timber structures – calculation of characteristic 5-percentile and mean values for the purpose of initial type testing and factory production control. CEN European Committee for Standardization, Brussels.
EN 338. (2016) Structural timber – Strength classes. CEN European Committee for Standardization, Brussels.
EN 384. (2016) Structural timber – Determination of characteristic values of mechanical properties and density. CEN European Committee for Standardization, Brussels.
FprEN 14081-2. (2017) Timber structures – Strength graded structural timber with rectangular cross section – Part 2: Machine grading; additional requirements for initial type testing. CEN European Committee for Standardization, Brussels.
Frese, M., Blaß, H.J. (2007) Characteristic bending strength of beech glulam. Mater. Struct. 40:3–13.
Frühwald, K., Schickhofer, G. (2005) Strength grading of hardwoods. 14th International Symposium on Nondestructive Testing of Wood, Hannover. pp. 198–210.
Giudiceandrea, F. (2005) Stress grading lumber by a combination of vibration stress waves and X-ray scanning. In: 11th International Conference on Scanning Technology and Process Optimization in the Wood Industry (ScanTech 2005), Las Vegas, NV, USA. pp. 99–108.
Glos, P., Lederer, B. (2000) Sortierung von Buchen- und Eichenschnittholz nach der Tragfähigkeit und Bestimmung der zugehörigen Festigkeits- und Steifigkeitskennwerte [Strength grading of beech and oak timber and derivation of strength and stiffness property values]. Report Nr. 98508. TU München, München, 125 pp.
Glos, P., Torno, S. (2008) Allocation of domestic maple, ash and poplar species into the European Standard EN 1912 Structural timber – strength classes – assignment of visual grades and species. (in German.) 06517_B. TU München, München.
Green, D.W., McDonald, K.A. (1993) Mechanical properties of red maple structural lumber. Wood Fibre Sci. 25:365–374.
Hübner, U. (2013) Mechanische Kenngrößen von Buchen-, Eschen- und Robinienholz für lastabtragende Bauteile: Dissertation. Technische Universität Graz, 424 pp.
Janowiak, J.J., Manbeck, H.B., Hernandez, R.H., Moody, R.C. (1997) Red maple lumber resources for glue-laminated timber beams. Forest Prod. J. 47:55–64.
Jeitler, G., Augustin, M., Schickhofer, G. (2016) BIRCH | GLT&CLT: mechanical properties of glued laminated timber and cross laminated timber produced with the wood species birch. In: Proceeding of WCTE 2016, Vienna, Austria. August 23–25. TU Verlag, Vienna.
Knorz, M., Schmidt, M., Torno, S., van de Kuilen, J.-W. (2014) Structural bonding of ash (*Fraxinus excelsior* L.): resistance to delamination and performance in shearing tests. Eur. J. Wood Prod. 72:297–309.
Kolling, C. (2007) Klimmahüllen für 27 Waldbaumarten [Climate shells for 27 forest tree specimens]. AFZ-DerWald: 1242–1245.
Kollmann, F.F.P., Côté, W.A. Principles of Wood Science and Technology: I. Solid wood. Springer-Verlag, Berlin, 1968.
Konak, A., David, W.C., Alice, E.S. (2006) Multi-objective optimization using genetic algorithms: A tutorial. Reliab. Eng. Sys. Safe. 91:992–1007.
Konnerth, J., Kluge, M., Schweizer, G., Miljković, M., Gindl-Altmutter, W. (2016) Survey of selected adhesive bonding properties of nine European softwood and hardwood species. Eur. J. Wood Prod. 74:809–819.
Kovryga, A., Stapel, P., van de Kuilen, J.W.G. (2016a) Optimizing characteristic properties of visually graded soft- and hardwoods lamellas for the glulam production. In: Proceeding of WCTE 2016, Vienna, Austria. August 23–25. TU Verlag, Vienna.
Kovryga, A., Stapel, P., van de Kuilen, J.W.G. (2016b) Tensile strength classes for hardwoods. In: Proceedings of 49th INTER and CIB Meeting, Graz, Austria.
Kretschmann, D.E., Green, D.W. (1999) Mechanical grading of oak timbers. J. Mater. Civ. Eng. 11:91–97.
Luedtke, J., Amen, C., van Ofen, A., Lehringer, C. (2015) 1C-PUR-bonded hardwoods for engineered wood products: influence of selected processing parameters. Eur. J. Wood Prod. 73:167–178.
Manbeck, H.B., Janowiak, J.J., Blankenhorn, P.R., Labosky, P., Moody, R.C., Hernandez, R. (1993) Performance of red maple glulam timber beams. Res. Pap. FPL-RP-519. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 33 pp.
Nocetti, M., Bacher, M., Brunetti, M., Crivellaro, A., van de Kuilen, J.W.G. (2010) Machine grading of Italian structural timber: preliminary results on different wood species. In: Proceeding of WCTE 2010, Riva del Garda, Trento, Italy. June 20–24.
Nocetti, M., Brunetti, M., Bacher, M. (2016) Efficiency of the machine grading of chestnut structural timber: prediction of strength classes by dry and wet measurements. Mater. Struct. 49:4439–4450.
Nocetti, M., Pröller, M., Brunetti, M., Dowse, G., Wessels, C. (2017) Investigating the potential of strength grading green *Eucalyptus grandis* lumber using multi-sensor technology. BioResources 12:9273–9286.
Oliver-Villanueva, J.-V., Quer, M., Becker, G. (1996) Influence of structural parameters on the nondestructive evaluation of ash timber (*Fraxinus excelsior* L.) Eur. J. Wood Prod. 54:109–112.
Ravenshorst, G.J.P. Species independent strength grading of structural timber. Technische Universiteit Delft, Delft, 2015.
Schmidt, M., Glos, P., Wegener, G. (2010) Verklebung von Buchenholz für tragende Holzbauteile. Eur. J. Wood Prod. 68:43–57.
Schmidt, M., Thönnißen, A., Knorz, M., Windeisen, E., Wegener, G. (2012) Relevant wood characteristics for gluing beech and ash with regard to discoloration. Eur. J. Wood Prod. 70:319–325.
Stapel, P., van de Kuilen, J.-W.G. (2014) Influence of cross-section and knot assessment on the strength of visually graded Norway spruce. Eur. J. Wood Prod. 72:213–227.
Torno, S., Knorz, M., van de Kuilen, J.W.G. (2013) Supply of beech lamellas for the production of glued laminated timber. In: 4th

International Scientific Conference on Hardwood Processing (ISCHP), Florence, Italy.
van de Kuilen, J.-W.G., Torno, S. (2014) Material properties of ash for application in glulam. (in German.) TU München, Munich, 82 pp.
Vega, A., Dieste, A., Guaita, M., Majada, J., Baño, V. (2012) Modelling of the mechanical properties of *Castanea sativa* Mill. structural timber by a combination of non-destructive variables and visual grading parameters. Eur. J. Wood Prod. 70:839–844.
von Wedel, K. (1966) Bohrspanuntersuchungen über das Gewicht des Bergahorn und des Spitzahornholzes [Investigations on the weight of increment cores from sycamore and norway maple]. Eur. J. Wood Prod. 24:329–338.
Z-9.1-679. (2013) German technical building approval issued by DIBt for “Glulam from beech wood and beech hybrid glulam beams” (in German), approval issued first on 07. Oct. 2009; approval holder: Studiengemeinschaft Holzleimbau e. V., Germany. Issued by Deutsches Institut für Bautechnik (DIBt), Germany.

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III Paper III - Strength grading of hardwoods using transversal ultrasound

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Strength grading of hardwoods using transversal ultrasound

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Abstract

Detection of local wood inhomogeneities is important for accurate strength and stiffness prediction. In hardwood specimens, visual characteristics (e.g. knots or fibre deviation) are difficult to detect, either with a visual surface inspection or by the machine. Transversal ultrasound scan (TUS) is a non-destructive evaluation method with high potential for hardwoods. The method relies on differences in ultrasound wave propagation in perpendicular to the grain direction. The aim of this study is to estimate and analyse the capabilities of TUS for defect detection in hardwoods and prediction of mechanical property values. In the current paper, the TUS was applied to the hardwood species European ash (*Fraxinus excelsior L.*), Norway maple (*Acer platanoides L.*) and sycamore maple (*Acer pseudoplatanus L.*). In total, 16 boards of both specimens were completely scanned perpendicular to the grain using a laboratory scanner with dry-coupled transducers. The measurements were processed to 2D scan images of the boards, and image processing routines were applied to further feature extraction, defect detection and grading criteria calculation. In addition, as a reference for each board, all relevant visual characteristics and mechanical properties from the tensile test were measured. Using the TUS global fibre deviation, the size and the position of the knots can be detected. Knottiness correlates to the strength properties similarly or even better compared to the manual knottiness measurement. Between the global fibre angle measured using TUS and measured on the failure pattern, no correlation could be found. The ultrasound modulus of elasticity perpendicular to the grain does not show any meaningful correlation to the elastic properties parallel to the grain. In overall, TUS shows high potential for the strength grading of hardwoods.

1 Introduction

Temperate European hardwoods, such as ash, beech and oak of structural size are known for their excellent mechanical properties, which also make them attractive for structural applications (Blass et al. 2005; Ehrhart et al. 2016a, b; Kovryga et al. 2019). To utilize the advanced mechanical properties, the high variation of this naturally grown material needs to be reduced. For the strength of wood and, particularly of hardwoods, visible local wood inhomogeneities are important. The same characteristics are more difficult to detect and measure with the available techniques compared to softwood (Olsson et al. 2018; Schlotzhauer et al. 2018).

The relationship between the grading criteria and the mechanical properties, as well as application of grading methods, differ between softwoods and hardwoods. The most accurate strength prediction method, at least for softwoods, is achieved by means of machine strength grading. The grading machines can explain up to 62% of the strength variation (Bacher 2008). For hardwoods, machine grading allows only limited prediction accuracy. Models based on dynamic modulus of elasticty (MOE_{dyn}), which is the most common criterion for the strength prediction, show R^2 values between 0.18 and 0.36 (Nocetti et al. 2016; Ravenshorst 2015). Higher prediction accuracy can be achieved only if MOE_{dyn} is combined with visually measured knottiness (Frühwald and Schickhofer 2005; Kovryga et al. 2019). Machine detection of the knottiness works less accurate for hardwoods compared to softwoods. Grading machines that use X-ray for the knot detection are limited because of the low contrast between the knots and clear wood (Giudiceandrea 2005). Other methods are currently not available for the strength grading purposes.

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Fibre deviation is another important criterion for the grading of hardwoods if strength is regarded. Generally, fibre deviation can be separated into local and global fibre deviations. Changes in local fibre flow are caused by local wood inhomogeneities, such as knots, bark inclusions, or top rupture, whereas the global fibre deviations are observable over the entire length of the wood specimen. For knot-free specimens, the variation in strength values is still high as evidenced by a number of publications (e.g. Ehrhart et al. 2016a, b; Kovryga et al. 2019). For those specimens, changes particularly in local fibre direction have major impact on the strength. However, the visible fibre angle provides no reliable results for the strength prediction (Frühwald and Schickhofer 2005). The machine detection of the fibre deviation by means of different non-destructive techniques has recently been in the scope of the study. For softwoods, the multi-sensory systems, able to detect the fibre deviation by means of laser scaning (tracheid effect), are available (Olsson et al. 2013). More recent results show the potential of such measurements for hardwoods, particularly for oak (Olsson et al. 2018). Application of other NDT techniques to hardwoods, such as thermal conductivity measurement (Daval et al. 2015) and automated visual analysis of the spindle patterns (Ehrhart et al. 2018) has been on the research agenda.

The usual way to use ultrasound for strength grading is to determine the velocity of the ultrasound wave in direction longitudinal to the grain and thus MOE_{dyn} (Sandoz 1989). Ultasound has the potential for detection of local wood inhomogeneities and thus improved strength grading. By applying ultrasound perpendicular to the grain direction, defects in wood can be detected. Transversal ultrasound scan (TUS) has been reported to detect knots, bark inclusions and other inhomogeneities in softwoods and some Northern American hardwoods in pallet parts (Kabir et al. 2002, 2003) and in structural timber (Machado et al. 2004). Ultrasound also provides information on the growth ring alignment. Propagation of the ultrasound wave differs between the radial and tangential growth ring orientations (e.g. Bucur 2006). Yaitskova and van de Kuilen (2014) provide an analytical model that links ultrasound wave propagation and growth ring orientation, so-called radial-tangential profile (RT-profile), and also highlights the possible application of TUS to the strength grading.

The aim of the present study is to analyze the potential of TUS for grading of European hardwoods, ash and maple. The definition and application of the novel grading criteria are of particular interest. The possibility to detect the major grading criteria—knots and the fibre deviation—and relate them to the mechanical properties are within the scope of the study.

2 Materials

To study the potential of ultrasound scan, a total of 79 boards of European hardwoods, namely European ash (*Fraxinus excelsior* L.), Norway maple (*Acer platanoides* L.) and sycamore maple (*Acer pseudoplatanus* L.), were used. Table 1 gives an overview of the selected specimens and their cross-section size. In total, 16 ash and maple boards out of the 79 boards were scanned with high resolution (5 × 5 mm), and 63 maple boards were scaned with coarse grid to evaluate the relationship between the ultrasound MOE perpendicular to the grain and tensile E_0. The selected specimens are part of a larger sampling presented in Kovryga et al. (2019) for hardwoods. The material can be considered representative of the selected species grown in central Europe. The boards were selected in a way that different wood features, such as the presence of pith, knots, fibre deviations and defect-free specimens, were present in a sample.

Table 1 Number, dimensions and mechanical properties of scanned European ash (*Fraxinus excelsior* L.) and maple (*Acer* spp.) boards

Wood species	Number (n)	Cross-sections	Scan length	*tKAR* (–)		ρ (kg/m³)		E_0 (GPa)		f_t (MPa)	
		depth × *width* (*b* × *h*) (mm × mm)	(mm)	μ	s	μ	s	μ	s	μ	s
Ash	3	30 × 125	1125	0.090	0.081	692	43	16.9	1.5	71.0	17.8
	4	35 × 125	1125								
Maple	2	25 × 125	1125	0.208	0.117	664	23	14.1	1.8	39.1	15.8
	3	30 × 125	1125								
	4	35 × 125	1125								
	63[a]	35 × 100	900	0.151	0.175	676	27	13.5	2.0	51.6	25.0
Total	79										

[a]Scanned with a coarse grid to evaluate relationship between $E_{us,90}$ and E_0

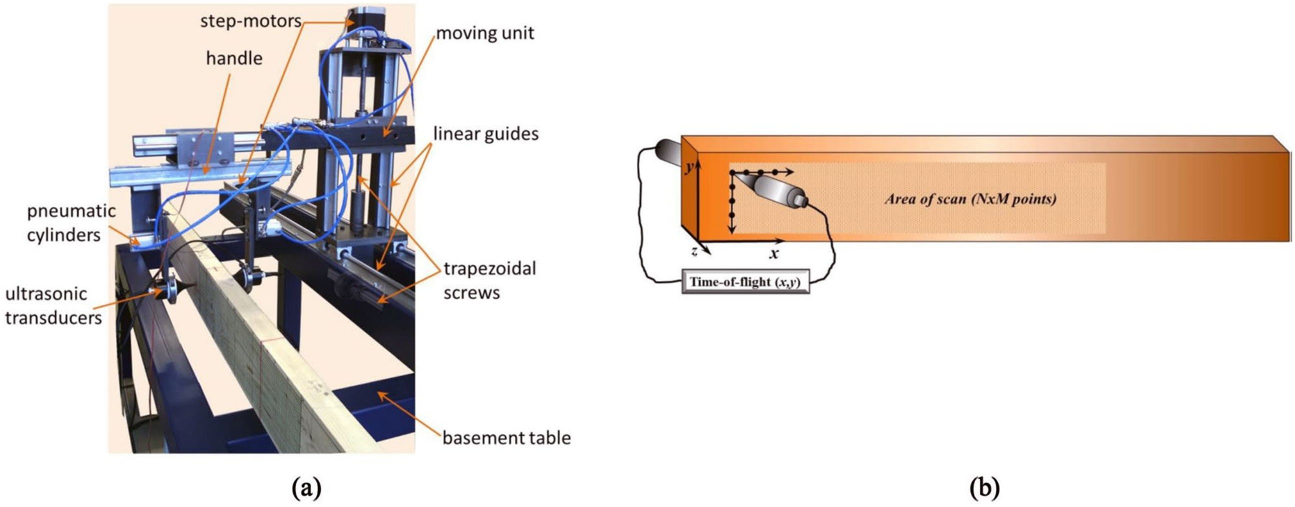


Fig. 1 Mechanical structure of TUS (**a**) and the measuring geometry (**b**) (Yaitskova et al. 2015)

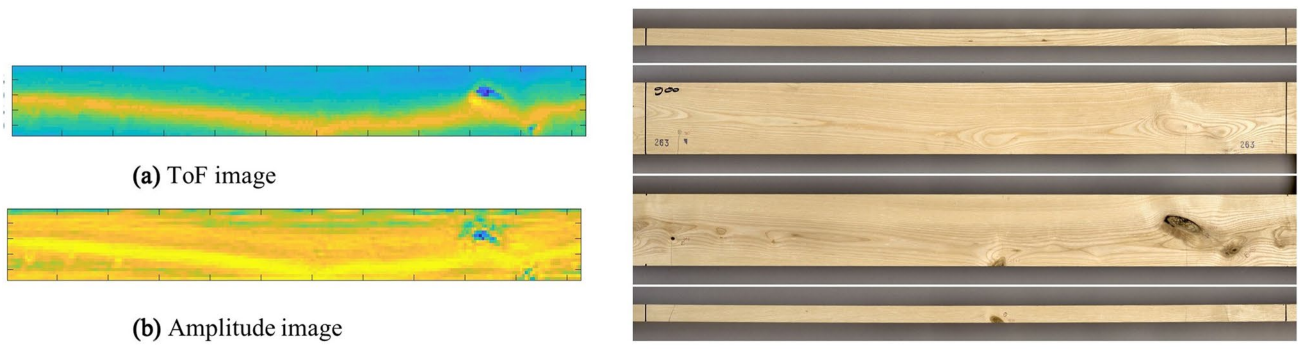
3 Methods

3.1 Transversal ultrasound scan (TUS)

The hardwood specimens were scanned using a laboratory scanner developed at the TU Munich (Fig. 1). The measuring unit (including ultrasound transducers) is moved along the specimen in x- and y-direction within the scan area. Measuring unit is used to measure and generate longitudinally polarized ultrasound signal included Pundit Lab+ with two dry-contact piezo-ceramic transducers, with a central frequency of 54 kHz from PROCEQ SA (Schwerzenbach, Switzerland). For the tested hardwoods, the wavelength corresponding to 54 kHz oscillation frequency in the direction perpendicular to the grains varies from 22 to 27 mm. The tested species (25–35 mm thickness) do not deceed the wavelength.

For each specimen, the area of 9 times the width (h) of the board was scanned by the device. 16 boards were scaned with high resolution (5 mm × 5 mm) resulting in a total of 82,800 measuring points. For the large maple sample (N = 63), the propagation of ultrasound signal was measured in 150 mm distance over the length of the board in four rows, with a space of 22.5 mm in between. In total, 28 measurement points were measured for each board. Those specimens were used to evaluate the relationship between the ultrasound MOE perpendicular to the grain and tensile MOE.

For each measuring point, different parameters of US signal—Time-of-flight (ToF), amplitude, energy, and spectral density—were calculated. For each parameter, a 2D image was generated and used to distinguish between



(a) ToF image

(b) Amplitude image

(c) Reference image

Fig. 2 Scan images for the European ash (*Fraxinus excelsior* L.) specimen Nr. 263 **a** time-of-flight (ToF) and **b** amplitude in comparison to the images of the scan area acquired on all four surfaces **c**

the wood features and clear wood using image processing algorithms and optimization routines (Fig. 2). For the current analysis, only ToF is used. When the signal exceeds the threshold defined as the noise multiplied by the factor of 3, which corresponds to 15 mV, the time is registered as ToF. The threshold value was found experimentally. Based on cluster analysis, it is concluded that for 54 kHz transducer only time-of-flight provides sufficient results for the defect detection. Other parameters (such as amplitude in Fig. 2b) did not provide any additional information on the defects.

3.2 Processing of ultrasound images

3.2.1 Image processing

In the current study, the feature detection includes two major targets: (1) detection of the global fibre deviation (minimum of RT-profile) and (2) detection of defects such as knots. Figure 3 visualizes major steps in processing of ultrasound signals starting with the measurement of ultrasound signal, followed by signal processing and then visualization and image processing steps required to segment the selected wood features (knots and alignment of fibres) out of the image. Each board is processed separately. For implementation of the algorithm, MATLAB R2016b and MATLAB Image Processing Toolbox R2016a (Mathworks, Natick, MA, USA) were used. The major steps are highlighted below:

1. RT-profile extraction
   In the original time-of-flight (ToF) image, beside the wood features, the macroscopic growth ring orientation can be observed. The speed of ultrasound wave differs depending on the propagation direction. It is higher in radial than in tangential direction. These differences between radial and tangential orientation, named RT-profile, are shown in Fig. 2a as gradient. This alignment coincides with the position of the knots and needs to be filtered. Yaitskova and van de Kuilen (2014) suggested an analytical approach to extract the profile. However, this approach requires fitting the polynomial to each tested specimen. In the current study, the RT-profile was restored by applying the median filter with the 3×10 mask to the ToF image and extracting it (Eq. 1). Applying a filter over the length allowed to exclude local wood features, such as knots. A similar approach was chosen by Machado et al. (2004) to normalize the wave parameters and reduce the influence of structural features on timber pieces.

$$D(x, y) = M_{tof}(x, y) - F(x, y) \quad (1)$$

   where D is a filtered image, M_{tof} is original image and F is a medium filter applied to it.
2. Image pre-processing
   Extraction of the profile increased the noise level in the image. To improve the segmentation performance, blurring using "Wiener filter" was applied to the images after RT-profile extraction. The Wiener filter provides a good solution for noisy images by adaptively tailoring itself to the local image variance. At locations with larger variance, only little smoothing is done; where the variance is little, more smoothing is performed. The mask of 3×10 pixels was chosen for the filtering. This means that the filter was applied in 10 pixels over the length of the board and 3 pixels along the width.
3. Segmentation
   Segmentation is the process of object extraction out of the image. Various algorithms, such as threshold techniques, texture-based algorithms, and wavelet-based techniques, are available. Algorithms are suitable to some specific use cases. Threshold techniques are the most common and frequently used techniques for low noise levels. For the current study, segmentation was done using global threshold value. A binary map is created by the global thresholding technique. By exceeding

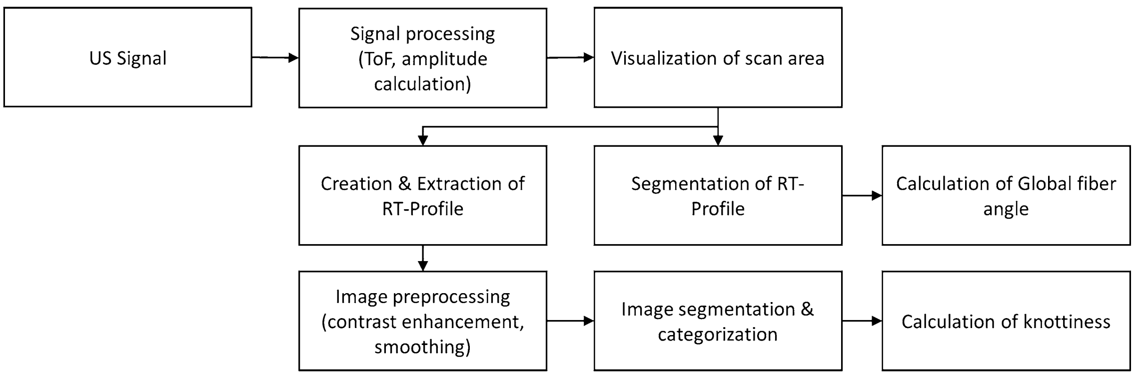


Fig. 3 Algorithm for the processing of the ultrasound images

a certain threshold value, pixels are assigned to defects or to the clear wood. The map is created as follows:

$$B_{tof}(x,y) = \begin{cases} 1 \ \ if\ D(x,y) \geq T, defect \\ 0 \ \ if\ D(x,y) < \ T, clearwood \end{cases} \quad (2)$$

Threshold (T) is a threshold value calculated for each single board as follows:

$$T = \mu \pm s \quad (3)$$

where μ is the mean value and s standard deviation of values in filtered image D (presented in Eq. 1).

4. Classification

Classification is an important step to assign the object to the specific defect type based on the features of the segmented region. The boards included mostly knots and drying cracks in knots. No cracks were observed within the boards. Due to the low number of defect classes (clear wood vs knots) and only limited number of boards, no specific classification routine has been applied. Applying classification routines such as k-NN-classifier (k-nearest neighbor) or neural networks might improve the classification result, but would require larger data sets.

3.2.2 Detection of RT-profile

Each measurement of the ultrasound wave between the sender and receiver integrates both the macroscopic profile and the effect of wood features. Such overlapping may lead to unreliable defect detection and classification, as well as some difficulties in profile detection.

Different solutions were tested for the RT-profile detection. One possibility to detect the RT-profile is to calculate the minima of the ToF at each single crosscut over the length of the test sample. Here, for some crosscuts, instead of the minimum of the RT-profile, the wood inhomogeneities were detected. In addition, image processing techniques and, in particular, edge detection algorithm were tested for the fibre alignment detection. Edge detection uses discontinuities in brightness to detect the boundaries of the object. Such contrast is observable at the minima of the RT-profile. However, the presence of knots and in some cases low contrast did not allow for the continuous and consistent fibre alignment identification.

The best solution was to detect the RT-profile by calculating the weighted minimum of ToF at a given point over the length of the board. The weight assured that abrupt changes in RT-profile do not occur. The minimum of RT-profile in position x is calculated using below equation:

$$P_x = \min\left(W(x,y) \cdot M_{tof,x}\right) \quad (4)$$

The weights W at the length coordinate x are calculated using Eq. (5).

$$W(x,y) = \left(1 + \frac{\left|P_{(x,y)} - P_{x-1}\right|}{z}\right) \quad (5)$$

where P_{x-1} position of the minimum of the RT-profile in previous x position and z-distance between the RT-profile and board edge.

The calculation procedure is performed stepwise from the beginning of the board to the end. The selected approach ensures a continuous path of the RT-profile within the board. Figure 4 shows exemplarily the minima of the detected RT-profile over the length of the board.

The grain angle is calculated as follows:

$$\alpha_{us} = \tan^{-1}\left(\frac{\Delta y}{\delta}\right) \quad (6)$$

where δ is window size used for the calculation of the fibre angle and Δy is the distance between the minimum and maximum coordinates of the RT-profile over the width of the specimen (along the y-axis) between the beginning (P_x) and the end of the window ($P_x + \delta$). Window size was set to 150 mm.

3.2.3 MOE perpendicular to the grain

Modulus of elasticity perpendicular to the grain ($E_{us,90}$) was also calculated and was done based on the information on the density and the ultrasound velocity, as shown in Eq. (7):

$$E_{us,90} = v_{us} \cdot \rho \quad (7)$$

3.3 Reference measurements

For the validation of the TUS results, the visual quality of boards was assessed by measuring size and location of knots (d > 5 mm), cracks and fibre deviation. To quantify the knottiness, the *tKAR* (*total Knottiness Area Ratio*) parameter was used. *tKAR* is calculated as area of knots appearing in a 150 mm large window, projected on the cross sectional area.

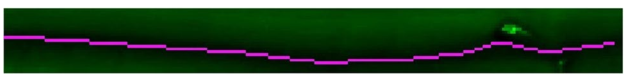


Fig. 4 Minimum of the RT profile representing the fibre for the European ash (*Fraxinus excelsior* L.) specimen 263

The overlapping areas are counted once. The fibre deviation was determined on the failure pattern after the destructive test had been performed. After conditioning of the samples under the reference conditions 20 °C and 65% relative humidity, each scanned board was tested in tension parallel to the grain according to EN 408 (2010). Thus, tensile strength and stiffness were also determined. Fibre deviation is defined as an angle with the longitudinal axis of the sawn piece and is measured in % (grain angle). The angle was measured on the surface of the larger side of the board.

4 Results and discussion

Ultrasound transversal to the grain scan allows the detection of characteristics relevant for the strength of hardwoods. As already mentioned, knots and global fibre deviation can be detected and extracted from the ultrasound scan images. The results and some pre-processing steps are illustrated in Fig. 5 for ash specimen. Knots can be visualized in ultrasound scan images. Furthermore, the global fibre deviation can be observed and detected. The visibility of the fibre deviation is referred to the differences in the ultrasound wave propagation in radial and tangential direction. The knot detection does not always work smoothly.

4.1 Knottiness

The knottiness from the ultrasound image shows a high correlation to the visually measured knottiness ($r = 0.791$, Table 2). The scatter shows a positive relationship between KAR values from TUS measurement and tKAR for which a clear trend line can be registered (Fig. 6). It also appears that for one specimen the knottiness was detected, although no knots were visually observable within the specimen. By studying the test specimen carefully, pith was detected on the surface of the board with a groove that has led to an increase in time-of-flight value because of the missing contact between the surface and transducer. Applying classification routine would allow to avoid such misclassification and/or to classify such features separately. The selected approach would allow applying the classification to the detected object

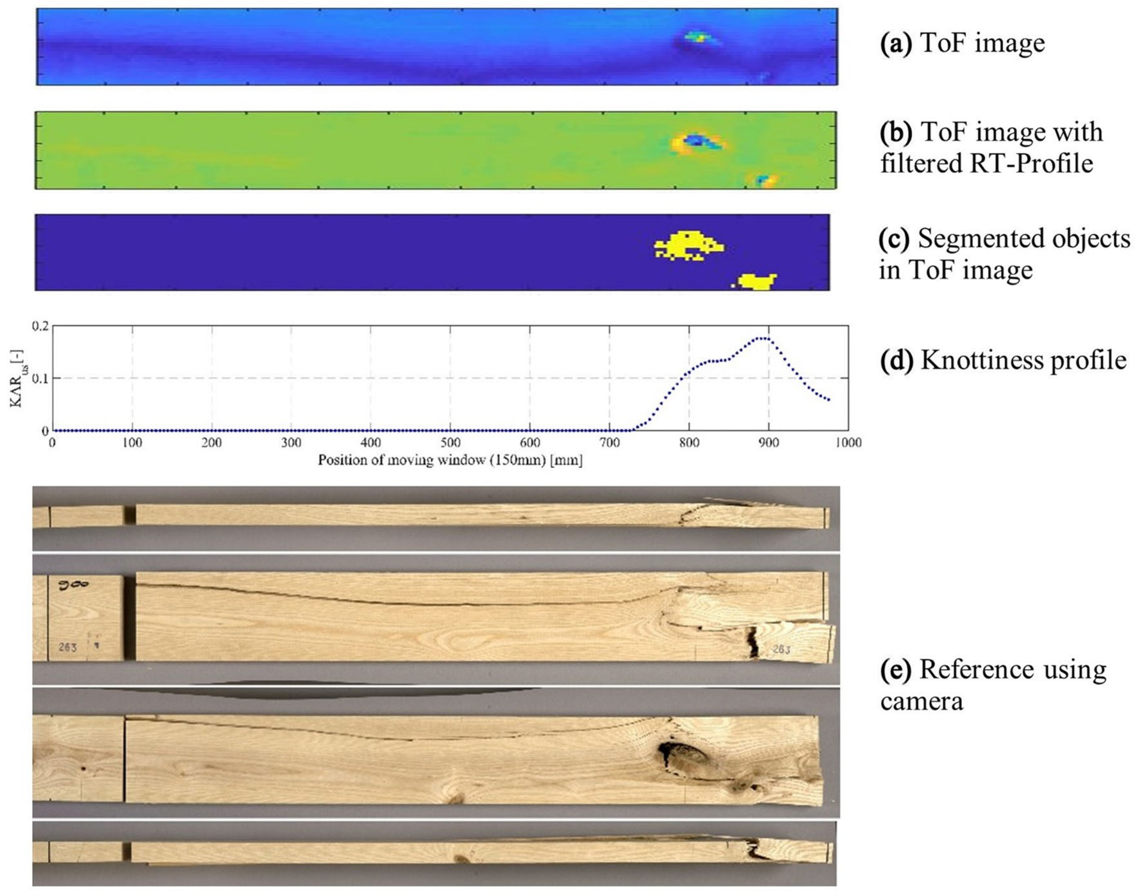


Fig. 5 Ultrasound scan of the European ash (*Fraxinus excelsior* L.) specimen no. 263 with **a** original ToF image; **b** ToF image with extracted RT-profile; **c** segmented objects in image; **d** knottiness profile; **e** reference image

Table 2 Correlations between ultrasound parameters, visual properties and mechanical properties for combined sample of European ash (*Fraxinus excelsior* L.) and maple (*Acer* spp.) ($N=16$)

	KAR_{us}	α_{us}	$tKAR$	α_{break}	ρ	E_0	f_t
KAR_{us}	1	0.353	0.791**	0.235	− 0.177	− 0.401	− 0.781**
α_{us}		1	0.459	0.814**	− 0.171	− 0.462	− 0.388
$tKAR$			1	0.516*	0.019	− 0.469	− 0.737**
α_{break}				1	− 0.170	− 0.484	− 0.341
ρ					1	0.508*	0.178
E_0						1	0.619**
f_t							1

*p < 0.05, **p < 0.01

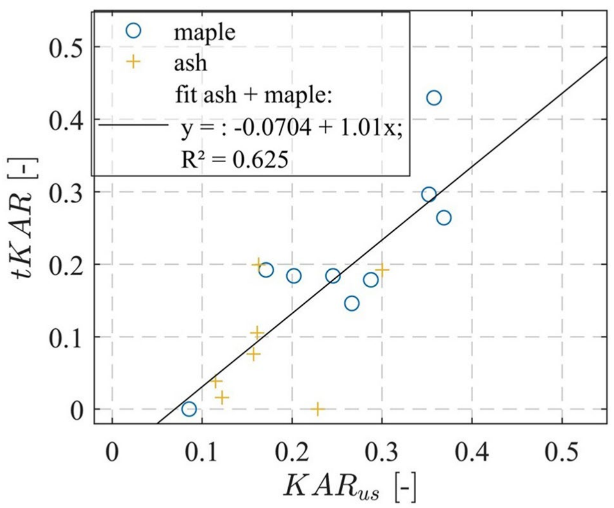


Fig. 6 Scatter plot between knottiness parameter KAR_{us} estimated from the ultrasound scan and the manually measured knottiness *tKAR*

and not to the single measurement. This spatial information would allow for increasing the accuracy.

The relationship between the knottiness parameters and tensile strength is shown in Fig. 7. For both TUS knottiness and manually measured knottiness *tKAR*, the tensile strength decreases with an increase in knottiness values. The prediction accuracy is in both cases high ($R^2 > 0.5$). TUS knottiness shows significantly higher R^2 values compared to the *tKAR*. The residuals scatter less around the regression line in case of the TUS knottiness compared to the visually determined knottiness. The results should be taken indicative only, as only a limited number of specimens were scanned.

4.2 Global fibre deviation detection

Fibre deviation is an important grading parameter for hardwoods. As previously shown, the ultrasound is able to detect the minimum of the so-called RT-profile that indicates the

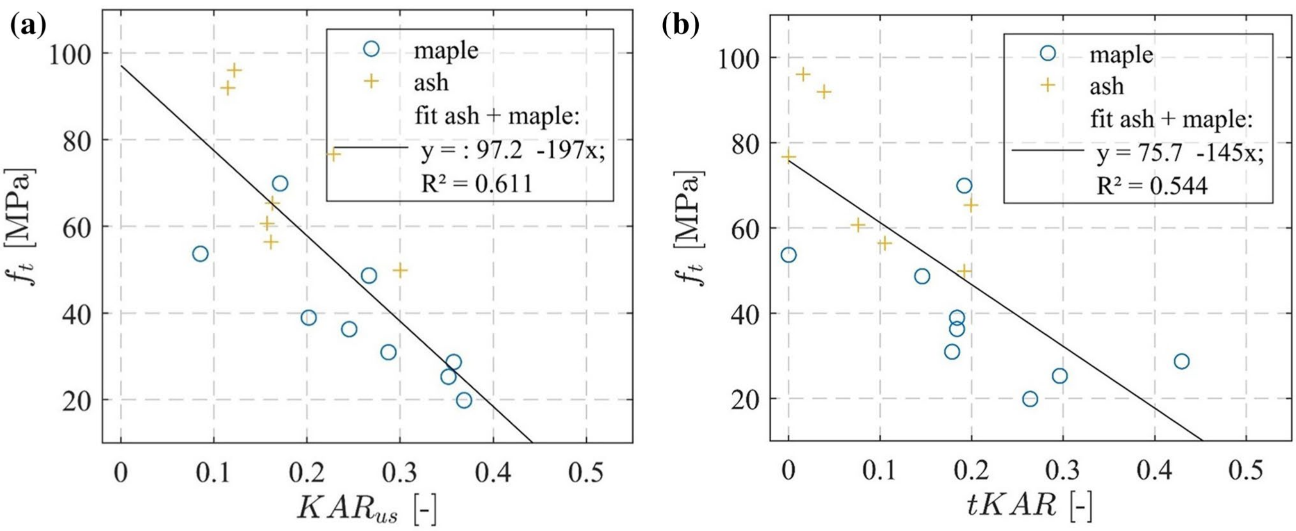


Fig. 7 Relationship between **a** knottiness measured using ultrasound device and tensile strength and **b** manually measured knottiness (*tKAR*) and tensile strength for European ash (*Fraxinus excelsior* L.) and maple (*Acer* spp.)

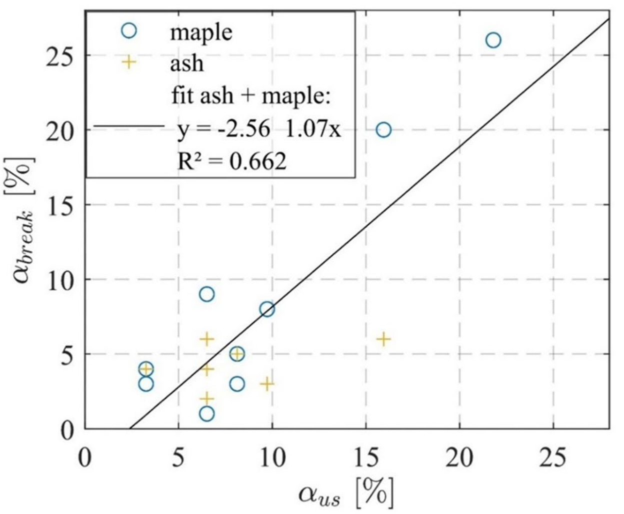


Fig. 8 Relationship between grain angle determined from the ultrasound image and the grain angle after the failure

alignment of fibres in the board. The ultrasound wave propagates in radial direction faster than in tangential direction. Figure 8 shows the relationship between fibre deviation measured using ultrasound and the fibre deviation detected manually by observing the failure pattern. The relationship is linear between the two measurement methods. For most of the specimens, the fibre angle ranged between 3 and 10%. For two boards greater fibre deviation was indicated using both methods. The small sample allows only indicative conclusions. The difference between the two measurements arises from the nature of the measurement. In case of ultrasound, the fibre angel measurement is an integral over the depth of the board.

Relationship between fibre angle and tensile strength is similar for both measurements. A clear decrease in tensile strength for increasing fibre angle can be observed (Fig. 9). However, there is no significant correlation between the fibre angle (measured using TUS device and measured manually on the failure pattern) and strength (Table 2). For fibre deviations of 10% and lower, the residuals scatter largely around the regression line. In case of low fibre angles, other criteria, such as knots or local fibre deviations limit the mechanical properties. Local aberrations of fibres are not detected using ultrasound, as the detection is based on the RT-profile. In case of local fibre deviation, other methods, such as thermal conductivity measurement, might be more attractive.

4.3 Modulus of elasticity perpendicular to the grain

The relationship between ultrasound MOE perpendicular to the grain and tensile MOE longitudinal to the grain was observed on the small (ash and maple) and on the large dataset (maple only). For a small sample scanned over the free length of the board in tension test, no relationship between MOE_{dyn} perpendicular to the grain and mechanical properties (strength, stiffness) could be found. For the larger data set, measured with the coarse grid, the ultrasound parameters—ultrasonic MOE perpendicular to the grain ($E_{us,90}$)/the velocity of ultrasound wave (v_{us})—show low to medium correlation to the tensile strength (Table 3). The maximum value shows the best correlation

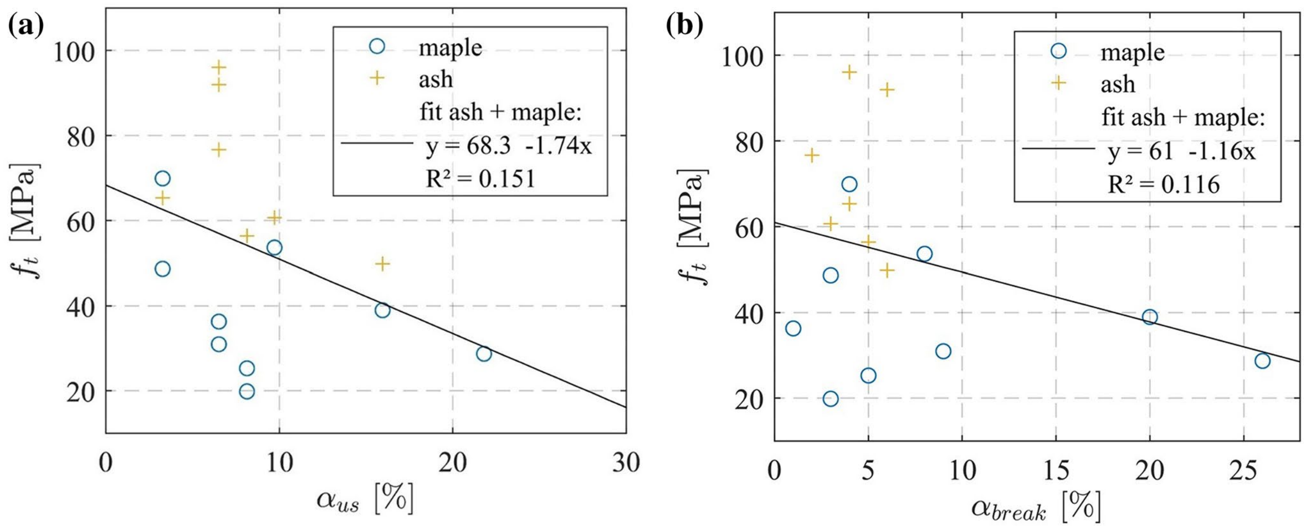


Fig. 9 Relationship between **a** grain angle measured using ultrasound device and tensile strength and **b** manually measured grain angle after failure and tensile strength for European ash (*Fraxinus excelsior* L.) and maple (*Acer* spp.)

Table 3 Correlations between parameters of ultrasound wave and mechanical properties for maple (*Acer* spp.) ($N=63$)

	$E_{us,90,mean}$	$E_{us,90,min}$	$E_{us,90,max}$	$v_{us,mean}$	$v_{us,max}$	ρ	E_0	f_t
$E_{us,90,mean}$	1	0.780**	0.778**	0.977**	0.777**	0.451**	− 0.087	− 0.344**
$E_{us,90,min}$		1	0.510**	0.763**	0.500**	0.510**	− 0.004	− 0.207
$E_{us,90,max}$			1	0.735**	0.986**	0.350**	− 0.217	− 0.417**
$v_{us,mean}$				1	0.764**	0.289**	− 0.038	− 0.282*
$v_{us,max}$						0.255**	− 0.189	− 0.391**
ρ						1	− 0.101	− 0.268*
E_0							1	0.705**
f_t								1

*p < 0.05, **p < 0.01

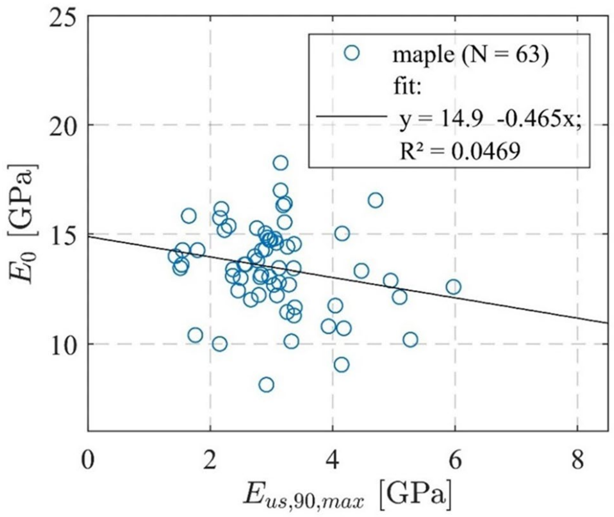


Fig. 10 Relationship between the ultrasound MOE perpendicular to the grain and E_0 for maple (*Acer* spp.) specimens ($N=63$)

to tensile strength. Density improves the correlation of ultrasound velocity only slightly. Between $E_{us,90,max}$ and E_0 (Fig. 10), no correlation can be found. The negative correlation and especially higher correlation of max. value of ultrasound velocity/ ultrasound MOE perpendicular to the grain can be explained as the values rather represent the local defects. The max. value of ultrasound velocity coincides with the presence of knots (if any are present in a board), as the velocity in sound knots is greater compared to the clear wood.

5 Conclusion

The current study examined the opportunities of ultrasound for defect detection in the hardwood species ash and maple. Ultrasound is able to detect the strength-reducing characteristics, fibre deviation, the knot position and its size. In particular, the knottiness parameter shows high compliance with the manually measured knottiness. High correlation between knottiness and strength values could also be achieved. Fibre deviation is an important parameter, especially for the knot-free hardwood specimens. For a sample with knot and knot-free specimens tested in the current study, no correlation between global fibre deviation (visually determined and using ultrasound) and strength could be found as presented in Frühwald and Schickhofer (2005). MOE perpendicular to the grain shows no relationship to the tensile MOE properties parallel to the grain. Because of the small sample sizes in this study, further tests on larger samples are required. Further investigations are necessary, not only regarding the different wood species but also regarding the technical aspects of meeting industrial requirements.

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References

Bacher M (2008) Comparison of different machine strength grading principles. In: Proceedings of COST E53 conference, Delft, The Netherlands, 29–30 October, pp 183–193

Blass HJ, Denzler, JK, Frese M, Glos P, Linsenmann P (2005) Biegefestigkeit von Brettschichtholz aus Buche (Bending strength of beech glulam). Karlsruhe: Univ.-Verl. (Karlsruher Berichte zum Ingenieurholzbau, Bd. 1)

Bucur V (2006) Acoustics of wood. Springer Series in Wood Science, 2nd edn. Springer, Berlin

Daval V, Pot G, Belkacemi M, Meriaudeau F, Collet R (2015) Automatic measurement of wood fiber orientation and knot detection using an optical system based on heating conduction. Opt Express 23(26):33529–33539. https://doi.org/10.1364/OE.23.033529

Ehrhart T, Fink G, Steiger R, Frangi A (2016a) Strength grading of European beech lamellas for the production of GLT & CLT. Paper 49-5-1. In: Proceedings of the 49th INTER & CIB meeting, Graz, Austria

Ehrhart T, Fink G, Steiger R, Frangi A (2016b) Experimental investigation of tensile strength and stiffness indicators regarding European beech timber. In: Proceedings of the world conference on timber engineering 2016 (WCTE 2016), Vienna, Austria, 22–25 August

Ehrhart T, Steiger R, Frangi A (2018) A non-contact method for the determination of fibre direction of European beech wood (*Fagus sylvatica* L.). Eur J Wood Prod 76(3):925–935. https://doi.org/10.1007/s00107-017-1279-3

EN 408 (2010) Timber structures: structural timber and glued laminated timber—determination of some physical and mechanical properties. CEN European Committee for Standardization, Brussels

Frühwald K, Schickhofer G (2005) Strength grading of hardwoods. In: Proceedings of the 14th international symposium on nondestructive testing of wood, Hannover, Germany, 2–4 May, pp 198–210

Giudiceandrea F (2005) Stress grading lumber by a combination of vibration stress waves and Xray scanning. In: 11th international conference on scanning technology and process optimization in the wood industry (ScanTech 2005), Wood Machining Institute, Walnut Creek, California, pp 99–108

Kabir MF, Schmoldt DL, Schafer ME (2002) Time domain ultrasonic signal characterization for defects in thin unsurfaced hardwood lumber. Wood Fiber Sci 34(1):165–182

Kabir MF, Schmoldt DL, Araman PA, Schafer ME, Lee S-M (2003) Classifying defects in pallet stringers by ultrasonic scanning. Wood Fiber Sci 35(3):341–350

Kovryga A, Schlotzhauer P, Stapel P, Militz H, van de Kuilen J-WG (2019) Visual and machine strength grading of European ash and maple for glulam application. Holzforschung. https://doi.org/10.1515/hf-2018-0142

Machado J, Sardinha R, Cruz H (2004) Feasibility of automatic detection of knots in maritime pine timber by acousto-ultrasonic scanning. Wood Sci Technol. https://doi.org/10.1007/s00226-004-0224-x

Nocetti M, Brunetti M, Bacher M (2016) Efficiency of the machine grading of chestnut structural timber: prediction of strength classes by dry and wet measurements. Mater Struct 49(11):4439–4450. https://doi.org/10.1617/s11527-016-0799-3

Olsson A, Oscarsson J, Serrano E, Källsner B, Johansson M, Enquist B (2013) Prediction of timber bending strength and in-member cross-sectional stiffness variation on the basis of local wood fibre orientation. Eur J Wood Prod 71(3):319–333. https://doi.org/10.1007/s00107-013-0684-5

Olsson A, Pot G, Viguier J, Faydi Y, Oscarsson J (2018) Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce (*Picea abies* L.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco.) and European oak (*Quercus petraea* (Matt.) Liebl/*Quercus robur* L.). Ann For Sci 75(4):33529. https://doi.org/10.1007/s13595-018-0781-z

Ravenshorst GJP (2015) Species independent strength grading of structural timber. Technische Universiteit Delft, Delft

Sandoz JL (1989) Grading of construction timeber by ultrasound. Wood Sci Technol 23(1):95–108. https://doi.org/10.1007/BF00350611

Schlotzhauer P, Wilhelms F, Lux C, Bollmus S (2018) Comparison of three systems for automatic grain angle determination on European hardwood for construction use. Eur J Wood Prod 40:118. https://doi.org/10.1007/s00107-018-1286-z

Yaitskova N, van de Kuilen JW (2014) Time-of-flight modeling of transversal ultrasonic scan of wood. J Acoust Soc Am 135(6):3409–3415. https://doi.org/10.1121/1.4873519

Yaitskova N, Nadkernychnyy Y, Franjga R, Monroy Gonzalez Plata R (2015) TUS: a breadboard for development of new wood grading algorithms using ultrasound. https://www.researchgate.net/publication/272664728_TUS_a_breadboard_for_development_of_new_wood_grading_algorithms_using_ultrasound

IV Paper IV - Strength and stiffness prediction with focus on different acoustic measurement methods

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ORIGINAL

Strength and stiffness predictions with focus on different acoustic measurement methods

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Abstract
Strength grading is an important step for the production of homogenous and high-quality solid wood material. In particular, for hardwoods, the use of non-visible characteristics is indispensable. Dynamic MOE (E_{dyn}) is an important parameter widely used for grading of softwoods and applicable to hardwoods as well. There are two common ways to measure E_{dyn}—ultrasound (US) wave propagation and longitudinal vibration (LV) method. Both methods are used in practice, however, due to the different inherent measurement techniques, the results differ. The current paper analyses the stiffness and strength coefficients of determination for several temperate European hardwood species and emphasizes the differences between the two measurement systems. The performance was analysed with regard to grading techniques, testing modes for the mechanical properties (tension and bending) and wood qualities. For more than 2861 pieces of European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), European oak (*Quercus* spp.) and maple (*Acer* spp.), the E_{dyn} was measured using both techniques, and destructive tests (tension and edgewise bending) were applied. The results show that LV has higher coefficient of determination compared to the US E_{dyn}. The coefficient of determination for both methods and tensile application can be increased by calculating E_{dyn} with average density. Furthermore, the results support species-independent strength grading of hardwoods. Further research on the effect of different wood qualities and sawing patterns is required.

1 Introduction

Temperate hardwoods are very well known for their excellent mechanical properties, which make them favourable for structural purposes. As a naturally grown material, wood shows high variation in mechanical properties. Strength grading is a crucial step for the production of homogenous and high-quality solid wood material with defined material properties. Whereas the research on softwoods has led to the high acceptance of the machine strength grading methods, the application of those methods to hardwoods is less frequent. The research activities in recent years in the field of strength grading and engineered wood products aimed to bridge knowledge gaps with regard to hardwoods.

Recent research activities have been focused on novel methods of non-destructive testing, as well as applying the established methods of machine strength grading to hardwoods. In focus of the mechanical strength grading, the dynamic MOE (E_{dyn}) can be highlighted as a major criterion of interest. E_{dyn} is a mechanical property of the material and describes the elastic behaviour of wood under dynamic cyclic stress and has been used to characterize wood material for decades (Kollmann and Côté 1968). The E_{dyn} application for the strength grading of structural timber dates back to Görlacher (1990) and is currently one of the most frequent methods for the machine strength grading of wood. Generally, there are two possibilities to determine E_{dyn}, which are: ultrasound (US) wave propagation and longitudinal vibration (LV) method. Both methods are related to the acoustic properties of wood. In the first case, an ultrasound wave signal is generated and the propagation in wood is measured, whereas in the other case, a stress wave is induced using a hammer and the eigenfrequency of wood is determined. Nowadays, the eigenfrequency method has established itself as very robust and is the most frequently used method. The characteristic vibrations in the board can be detected contact-free using a laser vibrometer (Giudiceandrea 2005).

As a grading parameter, E_{dyn} shows a high correlation to static MOE, for both softwoods (Bacher 2008) and

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hardwoods (Frühwald und Schickhofer 2005). Although for softwoods the correlation is higher, for hardwoods, the coefficient of determination of both US and LV measurement methods seems to be lower. The R^2 values reported for the strength prediction range from 0.18 to 0.36 for temperate hardwoods (Nocetti et al. 2016; Ravenshorst 2015) and are lower for the tensile strength prediction of temperate hardwoods shown for a variety of species ($R^2 < 0.25$) (Ehrhart et al. 2016; Glos and Lederer 2000; Green and McDonald 1993). For tensile strength, the coefficient of determination depends on the quality of the material. Westermayr et al. (2018) report a high R^2 value of 0.48 for low-quality beech lamella, compared to the value achieved for high-quality ones with 0.22 (Ehrhart et al. 2016). The quality difference refers to visual grading criteria such as growth inhomogenities, visible slope of grain as well as knots. This might imply that for timber of rejectable quality, higher grading accuracy could be achieved. In most publications, the E_{dyn} is determined using the LV. Therefore, questions arise regarding the performance of both methods and the differences between tensile and bending strength coefficient of determination. Frühwald and Hasenstab (2010) mention that the accuracy of the method is higher for LV.

The detection of the local inhomogeneities is crucial for hardwoods. LV and UV methods allow to determine the average wood quality. However, the local wood inhomogenities (such as knots and local slope of grain) are not detected using those methods. Both of them lead to a massive strength reduction (e.g., Kovryga et al. 2019). Therefore, the knot detection and measurement of the slope of grain using a variety of methods, such as laser scattering (Olsson et al. 2018), thermal conduction (Daval et al. 2015), automated image analysis (Ehrhart et al. 2018) and transversal ultrasound (Kovryga et al. 2020) are studied for the strength grading. However, due to their nature, those measurements have lower correlation to the elastic properties.

The present study aims to investigate the differences in the coefficient of determination between US and LV method on a large data pool of hardwood specimens tested at TU Munich in recent years. Both methods are compared regarding the correlation between E_{dyn} and tensile strength and stiffness. Special focus is given to the differences between the species, the ability to apply species-independent strength grading, and the ability for bending and tensile strength prediction. The species ash, beech, maple and oak representing hardwood species with different anatomical structure (ring-porous and diffuse porous) are investigated.

2 Materials

For the current study, in total 2681 specimens of European hardwoods—European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus* spp.) and maple (*Acer* spp.) were used. Table 1 gives an overview of the specimens and dimensions used. The length of the specimens varied between 3 and 5.5 m. The specimens originated from different projects run at TU Munich over two decades. Beech and oak were tested by Glos and Lederer (2000) within the hardwood strength grading project. Ash and maple tested in bending originate from the project on the assignment of those species to the bending strength classes (D-Classes) by Glos and Torno (2008a, 2008b). Tension test data of ash and maple were obtained by Kovryga et al. (2019) within the project on hardwood strength grading. Details are described in the mentioned publications.

Table 2 summarizes the mechanical properties of the tested hardwoods. The tested specimens are representative of the tested wood species and, particularly, for the growth region in Central Europe. The mechanical property values are comparable to the values given in other publications. Thus, for ash, the mean tensile strength values

Table 1 Overview of specimens and dimensions

Species	Bending			Tension		
	Cross-section ($b \times h$)	*N*	References	Cross-section ($b \times h$)	*N*	References
European ash (*Fraxinus excelsior*)	50×100; 50×150	324	Glos and Torno (2008a)	50×100; 50×150	259	
				25×85; 35×160; 30×100; 30×125; 35×100; 35×125	481	Kovryga et al. (2019)
European beech (*Fagus sylvatica*)	35×70; 60×120; 60×120; 60×180	224	Glos and Lederer (2000)	30×120; 30×160; 30×165	217	Glos and Lederer (2000)
Maple (*Acer* spp.)	50×100; 50×150; 50×175	459	Glos and Torno (2008b)	25×125; 30×100; 30×125	381	Kovryga et al. (2019)
				35×100; 35×125; 25×100		
Oak (*Quercus* spp.)	40×80; 60×120; 60×180	336	Glos and Lederer (2000)			
Total		1343			1338	

Table 2 Descriptive statistics of grading characteristics and mechanical properties from tension and bending test for European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus* spp.) and maple (*Acer* spp.) species

Species		Bending				Tension		
		Ash	Beech	Maple	Oak	Ash	Beech	Maple
N		324	224	459	336	740	217	381
$tKAR$ [−]	μ	0.055	0.102	0.075	0.175	0.067	0.146	0.119
	s	0.074	0.106	0.082	0.141	0.092	0.107	0.135
$E_{dyn,us,12}$ [GPa]	μ	16.1	18.1	15.1	13.4	16.5	17.7	16.7
	s	1.9	1.9	2.0	2.3	2.5	2.2	1.9
$E_{dyn,freq,12}$ [GPa]	μ	14.0	14.3	12.8	11.0	14.7	14.7	14.4
	s	1.8	2.8	1.7	2.1	2.4	2.0	1.7
MC [%]	μ	10.6	11.6	8.4	31.9	10.6	10.2	11.2
	s	0.9	0.6	0.9	9.5	1.0	0.4	0.6
ρ_{12} [kg/m^3]	μ	678	742	635	714	685	723	664
	s	49	38	41	55	57	41	45
$E_{0,12}$ [GPa]	μ	12.7	14.6	12.0	10.9	14.1	13.8	13.8
	s	1.8	2.4	1.9	2.8	2.7	2.5	2.2
f [MPa]	μ	69.8	65.3	56.3	56.1*	59.0	48.2	53.4
	s	16.1	20.7	18.7	17.2*	28.2	22.1	26.2

*f_m values for oak are adjusted to 12% MC; f_m ($\mu \pm s$) in wet conditions 38.7 ± 11.7 [MPa]

are comparable to the values reported by Frühwald and Schickhofer (2005). For beech, the values are lower compared to the ungraded tensile strength values reported by Ehrhart et al. 2016 ($f_{t,mean}$ = 66.7 MPa) and by Frühwald and Schickhofer (2005) ($f_{t,mean}$ = 62.2 MPa). On the other hand, the values considerably exceed the values reported by Westermayr et al. (2018) ($f_{t,mean}$ = 35.9 MPa) for low-quality beech lamella. Oak was tested at higher moisture content (MC), which was on average 31.9%. Therefore, the values are adjusted to the reference MC of 12% as described in Sect. 3.3. For species other than oak, only static MOE is adjusted to the reference MC; the strength is not adjusted as specimens are tested close to reference conditions (20 °C and 65% relative humidity). The bending strength values of oak adjusted to 12% MC are lower compared to beech or ash and are comparable to the ones reported by Faydi et al. (2017) with a mean value of 56 MPa and CoV of 39%.

3 Methods

3.1 Non-destructive measurements

For all the specimens, the grading characteristics were determined. The E_{dyn} was measured in two ways—using the ultrasound wave propagation and the longitudinal vibration (LV) method. The longitudinal US measurement was taken using Sylvatest device (Sandoz 1996) with a frequency of 20 kHz. During the non-destructive measurement, the runtime of the wave is measured longitudinal to the grain direction between the transmitting and receiving transducer. The E_{dyn} is calculated as a product of density ρ and ultrasound wave v using Eq. 1:

$$E_{dyn,us} = v^2 \cdot \rho \tag{1}$$

For the LV method, a hammer is used to generate stress waves. The signal is recorded by means of a microphone or an accelerometer. Both measurements are taken at the laboratory of the TU Munich for repeatability check, as they provide similar results. In industrial facilities, a laser vibrometer can be used to record vibrations contact-free. By applying the FFT-transformation, the eigenfrequency is calculated. The $E_{dyn,freq}$ is calculated by combining the first eigenfrequency (f) with length (l) of the specimen and density (ρ) measurement using the following equation:

$$E_{dyn,freq} = 4 \cdot l^2 \cdot f^2 \cdot \rho \tag{2}$$

The density is measured by weighing the specimen.

For temperate hardwoods, density usually shows no correlation to the tensile and bending strength (Ehrhart et al. 2016; Westermayr et al. 2018; Frühwald and Schickhofer 2005). Therefore, E_{dyn} was calculated using a constant density value to study the effect of eigenfrequency and ultrasound velocity on the strength properties. For each wood species, the average density from Table 2 was taken into account. The difference between the E_{dyn} calculated with individual density readings and E_{dyn} with an average density of the wood species is discussed in the paper.

To separate low- and high-quality specimens, the knottiness parameter $tKAR$ (total knottiness area ratio) is used. $tKAR$ is a parameter frequently used in scientific publications and in national visual grading standards, such as BS

4978. It is calculated as the area of knots appearing in a 150 mm long part of the specimen, projected on the cross-sectional area. The overlapping areas are counted once.

3.2 Destructive tests

The hardwood specimens were tested in tension and in bending according to the test specification of EN 408 (2010) valid at the time of testing. The bending strength and local MOE were measured in a four-point bending test. The test span between the two loading points was six times the depth of the cross-section. For local MOE, the deformation was measured over the length of five times the depth. The tensile strength was determined with the free test length of nine times the height and the gauge length for the tensile MOE measurement was five times the height.

3.3 Moisture content adjustment

The mechanical properties were adjusted to the reference conditions 20 °C and 65% relative humidity. For all species, the equation derived by Nocetti et al. (2015) on chestnut was used to adjust dynamic and static MOE. The procedure in EN 384 does not specify any adjustment factors for MC above 18%. For MOE below fiber saturation point (FSP), Eq. 3 was used.

$$E_{12} = \frac{E_u}{1 - 0.005(u - 12)} \tag{3}$$

where E_u is the MOE measured at a certain moisture content level and u is the moisture content.

For changes in MC above FSP, Eq. 4 was used:

$$E_{12} = \frac{E_u}{0.9} \tag{4}$$

The equation assumes a constant MOE value above FSP also shown by Unterwieser and Schickhofer (2011).

The bending strength (f_m) values are adjusted to the reference conditions by assuming a 1.4% increase in strength per 1% MC decrease up to fiber saturation point (Hernández et al. 2014). The selected factor is supported by the findings of Glos and Lederer (2000) for the tested sample who found the difference in bending strength between green and dry specimens of about 21%. The selected factor is designated on the safe side, as in some publications higher change rate is reported. Wang and Wang (1999) report a change rate of 3.9% in bending strength per 1% MC change for red oak.

3.4 Statistical analysis

For the statistical analysis, the linear regression and correlation analyses were used. To analyse the performance of LV and US for the strength and stiffness prediction, the samples were grouped by the destructive testing mode (bending, tension) after the grading and by the wood species. For each group, the correlation analysis was applied by calculating the Pearson correlation coefficient.

4 Results and discussion

4.1 Longitudinal vibration method vs. ultrasound measurement

Figure 1 shows the relationship between E_{dyn} from the US and LV measurements. Generally, high consistency between

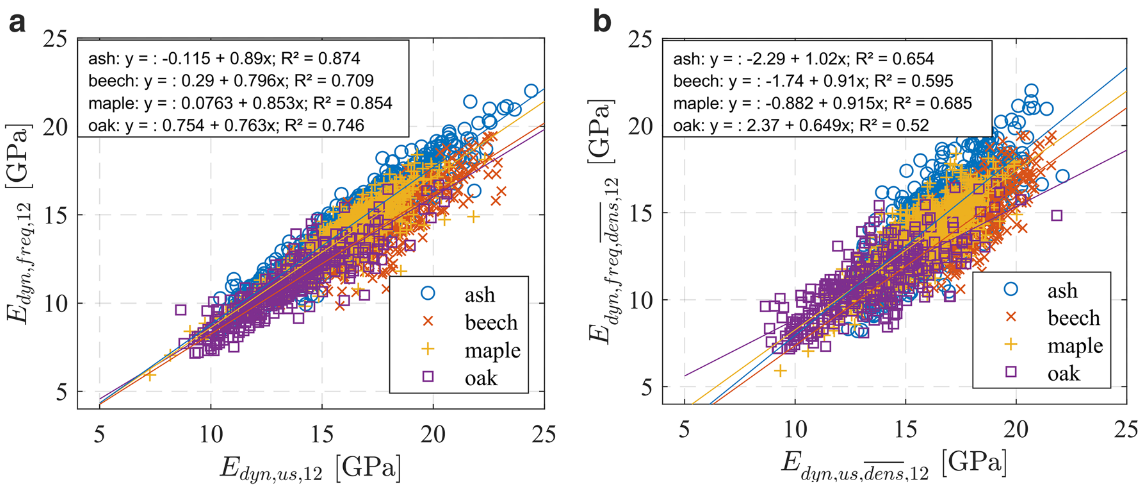

Fig. 1 Relationship between E_{dyn} from US measurement and E_{dyn} measured using LV method with E_{dyn} calculated **a** with individual density reading and **b** calculated with constant density value, grouped by the hardwood species

both measurements across the wood species can be observed. The coefficient of determination between ultrasound E_{dyn} and eigenfrequency E_{dyn} ranges between 0.7 for beech and 0.87 for ash. If the E_{dyn} is calculated using average density (Fig. 1b), the overall R^2 value drops and the scatter shows significantly higher variation. Therefore, individual density values provide a homogenizing effect on the relationship between the E_{dyn} from the US and LV measurements. Major differences in the prediction of grade determining properties, like strength and stiffness, are, therefore, expected for the E_{dyn} without considering the density.

4.2 Stiffness prediction

The coefficient of determination for the tensile and bending MOE is shown in Table 3. E_{dyn} from LV measurement shows higher R^2 values compared to the US measurement. Whereas for oak the difference is less pronounced, the difference for beech and maple increases up to max. 0.3. The prediction strength of static MOE drops for both E_{dyn} ($E_{dyn,freq,\overline{dens},12}$ and $E_{dyn,us,\overline{dens},12}$) calculated with average density.

The coefficient of determination between US E_{dyn} and LV E_{dyn} is compared for a combined hardwood species data set in Fig. 2 dependent on the testing mode. The LV E_{dyn} scatters less compared to the US measurement. For both measurements, the regression equation seems to predict tensile and bending MOE similarly well. The scatter has a similar shape. However, the variation around the regression line is higher for the correlation to the bending stiffness. For the specimens tested in tension, E_t shows larger scatter with values up to 22 GPa.

The possibility of combining the wood species for the species-independent strength grading is visualized in Fig. 3. For both testing modes (bending and tension), the population of temperate European hardwoods shows homogenous scatter. The values scatter approximately within the same range. For ash in tension, the stiffness is slightly higher compared to beech and maple. Furthermore, specimens show,

Table 3 Coefficient of determination (R^2) for the prediction of density, modulus of elasticity and strength from bending and tension tests for European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus* spp.) and maple (*Acer* spp.) species

	Bending			Tension		
	ρ_{12}	$E_{0,12}$	f_m	ρ_{12}	$E_{0,12}$	f_t
European ash						
ρ_{12}	1	0.234	0.036	1	0.298	0.034
$E_{dyn,us,12}$	0.415	0.651	0.119	0.424	0.658	0.148
$E_{dyn,freq,12}$	0.312	0.778	0.282	0.386	0.749	0.270
$E_{dyn,us,\overline{dens},12}$	0.008	0.467	0.092	0.054	0.509	0.149
$E_{dyn,freq,\overline{dens},12}$	0.002	0.568	0.269	0.047	0.591	0.296
MC	0.116	0.009	0.009	0.012	0.059	0.009
European beech						
ρ_{12}	1	0.066	0.034	1	0.172	0.010
$E_{dyn,us,12}$	0.369	0.386	0.202	0.475	0.625	0.188
$E_{dyn,freq,12}$	0.287	0.699	0.407	0.351	0.847	0.386
$E_{dyn,us,\overline{dens},12}$	0.038	0.350	0.187	0.103	0.575	0.246
$E_{dyn,freq,\overline{dens},12}$	0.039	0.661	0.393	0.054	0.772	0.471
MC	0.191	0.053	0.070	0.020	0.025	0.002
Maple						
ρ_{12}	1	0.078	0.017	1	0.031	0.029
$E_{dyn,us,12}$	0.238	0.666	0.163	0.364	0.319	0.007
$E_{dyn,freq,12}$	0.201	0.792	0.312	0.207	0.598	0.142
$E_{dyn,us,\overline{dens},12}$	0.005	0.573	0.144	0.009	0.348	0.054
$E_{dyn,freq,\overline{dens},12}$	0.002	0.674	0.285	0.002	0.558	0.263
MC	0.000	0.077	0.085	0.067	0.002	0.000
Oak						
ρ_{12}	1	0.007	0.009			
$E_{dyn,us,12}$	0.209	0.554	0.312			
$E_{dyn,freq,12}$	0.192	0.572	0.398			
$E_{dyn,us,\overline{dens},12}$	0.022	0.482	0.252			
$E_{dyn,freq,\overline{dens},12}$	0.025	0.521	0.345			
MC	0.083	0.000	0.028			

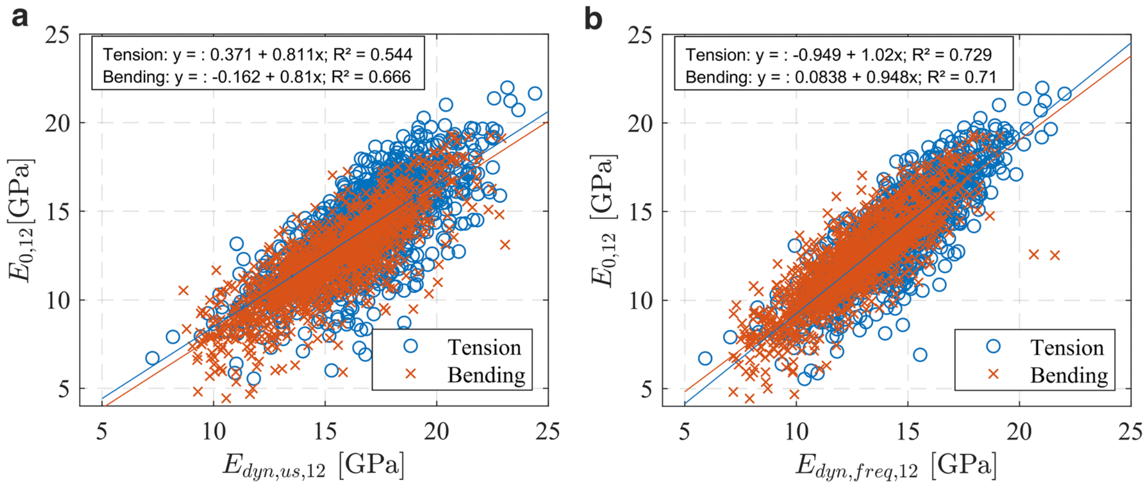

Fig. 2 Scatterplot between **a** E_{dyn} measured using US device and static MOE and **b** E_{dyn} measured using LV method and static MOE for all investigated hardwood species, split by the testing mode (bending, tension)

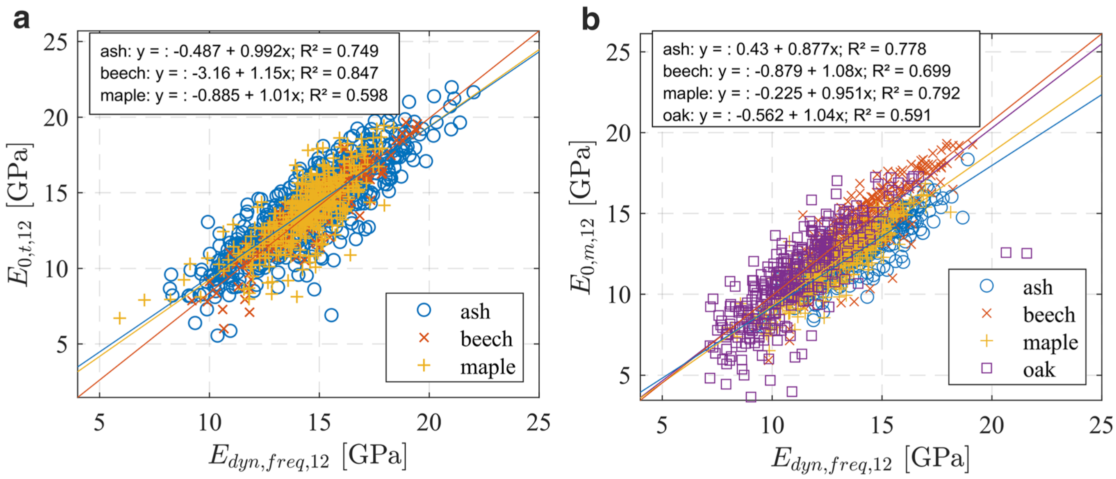

Fig. 3 Relationship between **a** E_{dyn} measured using LV method and tension MOE and **b** E_{dyn} measured using LV method and bending MOE, grouped by the hardwood species

in particular for tension test specimens, almost parallel slope of the regression line. The observation supports the approach by Ravenshorst (2015) regarding the applicability of the species-independent strength grading to the example of tension data.

4.3 Strength prediction

The bending and tensile strengths are predicted with US ($E_{dyn,us,12}$) less accurately compared to the LV ($E_{dyn,freq,12}$). The accuracy ranges between 0.007 and 0.312 for the US and 0.142 and 0.407 for the LV. The R^2 values between $E_{dyn,freq,12}$ and strength (f_t and f_m) are approximately two times higher compared to the values between $E_{dyn,us,12}$ and strength. These findings support the results of Frühwald and Hasenstab (2010), who came to the conclusion that E_{dyn} from LV is a better predictor for the tensile strength.

The scatter between E_{dyn} calculated with average density and tensile strength is visualized for the frequency measurement in Fig. 4. The scatter for the US shows a similar pattern but higher variation (not shown here). The values for all the species fall within the same range and support the idea of species-independent scatter. In particular, for the tensile strength, the scatter is very similar. The slopes of the regression lines are almost equal, allowing for a species-independent strength grading.

The use of ultrasound and eigenfrequency E_{dyn} depends on the density value used for the calculation of the E_{dyn}. If the average density value of the wood species is used for the calculation of E_{dyn} and not the individual density value,

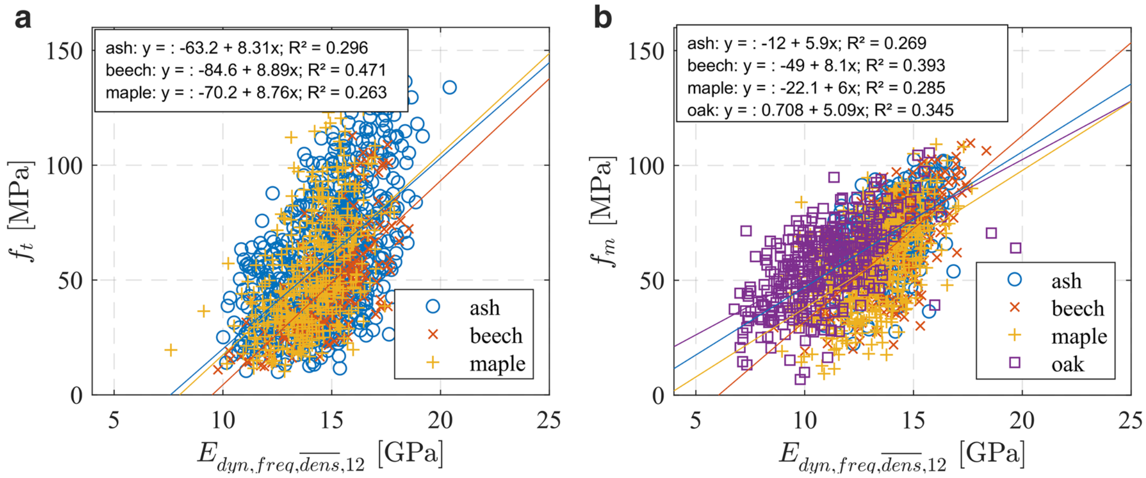

Fig. 4 Relationship between **a** E_{dyn} measured using LV and tensile strength and **b** E_{dyn} measured using LV and bending strength, grouped by hardwood species

the strength coefficient of determination increases for some samples. For specimens tested in tension, a clear increase in coefficient of determination is observable, while for the specimens tested in bending, the exclusion of density value leads to a slight drop in R^2 values (0.015 on average). The same results have been shown by Nocetti et al. (2016) on chestnut timber tested in bending. The coefficient of determination for LV bending strength prediction decreased from 0.24 to 0.15. This behaviour is most likely attributed not only to the testing mode but rather to specimen dimensions and sawing pattern used.

Figure 5 exemplarily visualizes the difference in coefficient of determination of the tensile strength using E_{dyn} calculated with average density and individual density for European ash. For the relationship between E_{dyn} calculated with average density and tensile strength, a scatter with less variation and steeper regression line can be observed. As a consequence of lower variation around the regression line, higher R^2 value can be achieved. By calculating with an average density, the variation in E_{dyn} is reduced. The density is a part of E_{dyn} calculation that shows either low correlation or no correlation to the timber strength. In the case of maple, the correlation is even negative ($r = -0.120$).

The observable differences in strength prediction are most likely attributed to the cross-section size and the sawing pattern used. This can be observed on the ash tested in tension which comprises two sub-samples. The first sub-sample includes timber of thicker cross-section (50 × 100 and 50 × 150) and cut with "cutting all around" (without pith) pattern and the second sub-sample includes smaller

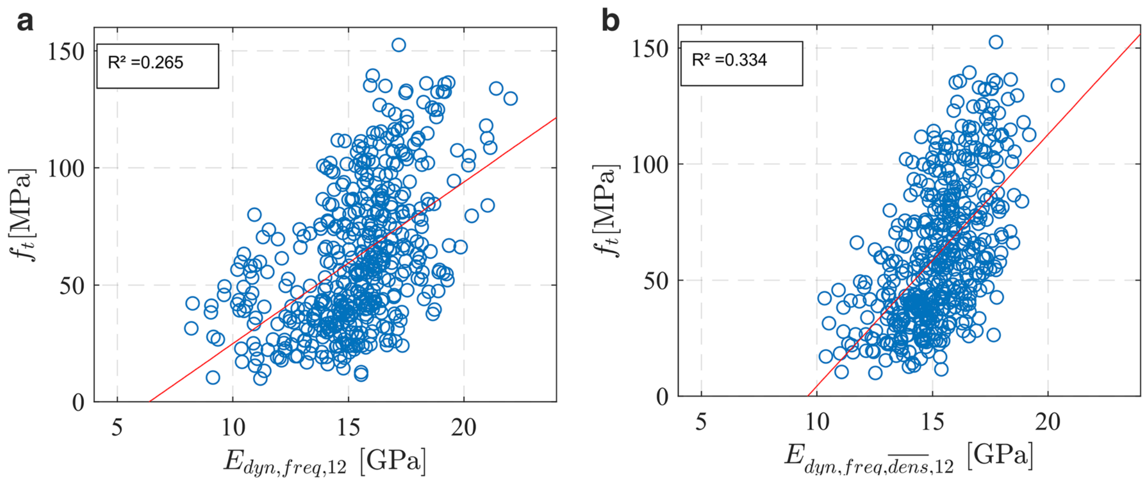

Fig. 5 Relationship between tensile strength and E_{dyn} measured by using LV method and calculated with the individual (**a**) and average density (**b**) for European ash (*Fraxinus excelsior*) sub-sample tested by Kovryga et al. (2019) ($N = 481$)

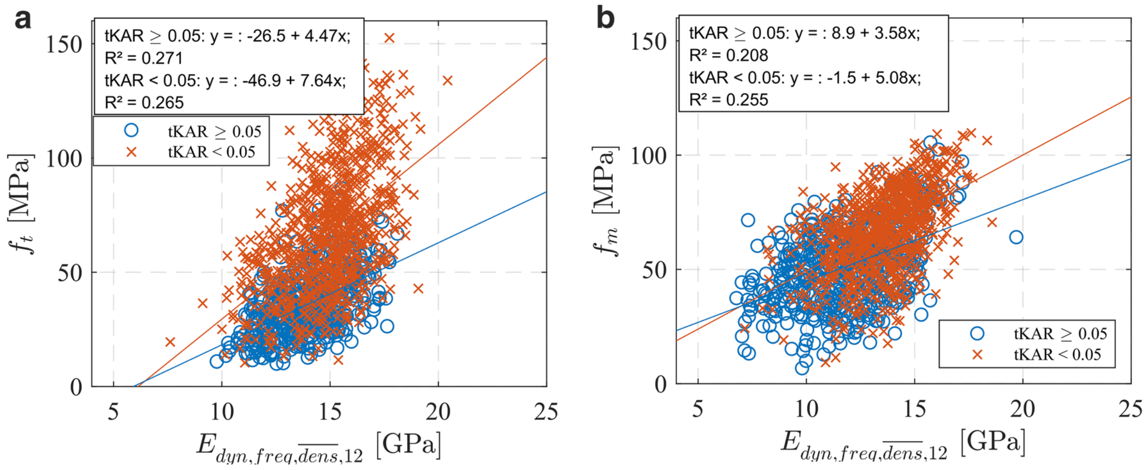

Fig. 6 Relationship between **a** E_{dyn} measured using LV and tensile strength and **b** E_{dyn} measured using LV and bending strength, for a combination of hardwood species, grouped in knot-free specimens ($tKAR < 0.05$) and specimens with knots ($tKAR > 0.05$)

cross-sections (25 × 85 to 35 × 165 tested by Kovryga et al. 2019, Table 1) cut with a sawing pattern that included the pith. For the larger samples, no significant difference in coefficient of determination using $E_{dyn,freq,12}$ and $E_{dyn,freq,\overline{dens},12}$ was observable. In contrast, for smaller ash dimensions, the coefficient of determination increased from 0.265 to 0.334 by using average density instead of individual reading. The juvenile wood present in the sawing pattern with pith is known for temperate hardwoods to have slightly higher density compared to the mature wood (e.g., Woodcock and Shier 2002; Gryc et al. 2008). Therefore, a higher share of pith specimens could negatively affect the applicability of the density to E_{dyn} calculation for strength prediction. For those specimens, higher density of juvenile wood increases the numeric value of the E_{dyn}, which would also indicate/evidence higher strength, which is obvioulsy not the case for juvenile wood. To make general conclusions and study the causes, a special testing program is required.

Additionally, the effect of the wood quality on the relationship between E_{dyn} and strength can be observed in Fig. 6. The wood quality was defined as knot-free specimens and specimens with $tKAR > 0.05$. For the tensile and bending strength predictions, the greater slope of the regression line is visible on the knotfree specimens. In the case of tensile strength, the difference is even more pronounced. Although the R^2 value does not differ significantly between knot-free ($tKAR < 0.05$) and specimens with knots, the variation of measured values around the regression line in the case of knot-free specimens is greater. For bending strength, the coefficient of determination is slightly higher.

5 Conclusion

In this paper, the differences between the coefficient of determination of the dynamic MOE measured by using US and LV methods were studied. The E_{dyn} measured by using LV results in higher coefficient of determination for the strength and stiffness. Nevertheless, the accuracy of the ultrasound E_{dyn} is high as well, especially for the MOE prediction. The results also support the findings of Ravenhorst (2015) for the species-independent strength grading for both bending strength and tensile strength. The same regression equation can be used to predict both tensile MOE and bending MOE with E_{dyn}. Furthermore, the effect of wood quality or knottiness of the wood on the grading accuracy was observed. Whereas for tension specimens the coefficient of determination did not differ much, the slope of the regression line and the scatter differ significantly. For tension test specimens, the use of average density in E_{dyn} calculation increases the coefficient of determination for strength prediction. This could be caused by smaller cross-sections of the tested specimens, as well as by the different sawing patterns. Further research is required to better understand the wave propagation in such specimens.

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References

Bacher M (2008) Comparison of different machine strength grading principles. In: Proceedings of COST E53 Conference, October 29–30, Delft, The Netherlands, pp 183–193

Daval V, Pot G, Belkacemi M, Meriaudeau F, Collet R (2015) Automatic measurement of wood fiber orientation and knot detection using an optical system based on heating conduction. Opt Express 23(26):33529–33539. https://doi.org/10.1364/OE.23.033529

Ehrhart T, Fink G, Steiger R, Frangi A (2016) Experimental investigation of tensile strength and stiffness indicators regarding European beech timber. In: Proceedings of the World Conference on Timber Engineering 2016 (WCTE 2016), August 22–25, Vienna, Austria

Ehrhart T, Steiger R, Frangi A (2018) A non-contact method for the determination of fibre direction of European beech wood (*Fagus sylvatica* L.). Eur J Wood Prod 76(3):925–935. https://doi.org/10.1007/s00107-017-1279-3

EN 408 (2010) Timber structures—structural timber and glued laminated timber—determination of some physical and mechanical properties. CEN European Committee for Standardization, Brussels

Faydi Y, Brancheriau L, Pot G, Collet R (2017) Prediction of oak wood mechanical properties based on the statistical exploitation of vibrational response. BioResources 12(3):5913–5927. https://doi.org/10.15376/biores.12.3

Frühwald K, Schickhofer G (2005) Strength grading of hardwoods. Proceedings of the 14th International Symposium on Nondestructive Testing of Wood, May 2–4, Hannover, Germany, pp 198–210

Frühwald K, Hasenstab A (2010) Zerstörungsfreie Prüfung von Laubholz in Holzbauprodukten und im eingebauten Zustand (Nondestructive testing of hardwood in structural timber products and when built-in) (In German). In: Fachtagung Bauwerksdiagnose, February 18–19, Berlin, Germany, pp 17–18

Giudiceandrea F (2005) Stress grading lumber by a combination of vibration stress waves and Xray scanning. In: 11th International Conference on Scanning Technology and Process Optimization in the Wood Industry (ScanTech 2005), Wood Machining Institute, Walnut Creek, California, pp 99–108

Glos P, Lederer B (2000) Sortierung von Buchen- und Eichenschnittholz nach der Tragfähigkeit und Bestimmung der zugehörigen Festigkeits- und Steifigkeitskennwerte (Strength grading of beech and oak sawn lumber and determination of characteristic strength and stiffness values). Report No. 98508, Holzforschung München, Munich

Glos P, Torno S (2008a) Allocation of ash and poplar of German origin to EN 1912. Report No. TG1/0508/16, TU München, Munich

Glos P, Torno S (2008b) Allocation of maple of German origin to EN 1912. Report No. TG1/1108/26, TU München, Munich

Görlacher R (1990) Klassifizierung von Brettschichtholzlamellen durch Messung von Longitudinalschwingungen (Grading of glulam lamellas by longitudinal vibration measurement), Dissertation. Universität Karlsruhe, Karlsruhe

Green DW, McDonald KA (1993) Mechanical properties of red maple structural lumber. Wood Fibre Sci 25(4):365–374

Gryc V, Vavrčík H, Rybníček M, Přemyslovská E (2008) The relation between the microscopic structure and the wood density of European beech (*Fagus sylvatica* L.). J Forest Sci 54(4):170–175

Hernández RE, Passarini L, Koubaa A (2014) Effects of temperature and moisture content on selected wood mechanical properties involved in the chipping process. Wood Sci Technol 48(6):1281–1301. https://doi.org/10.1007/s00226-014-0673-9

Kollmann FFP, Côté WA (1968) Principles of wood science and technology I. Solid wood. Springer-Verlag, Berlin

Kovryga A, Schlotzhauer P, Stapel P, Militz H, van de Kuilen J-WG (2019) Visual and machine strength grading of European ash and maple for glulam application. Holzforschung. https://doi.org/10.1515/hf-2018-0142

Kovryga A, Khaloian Sarnaghi A, van de Kuilen JWG (2020) Strength grading of hardwoods using transversal ultrasound. Eur J Wood Prod. https://doi.org/10.1007/s00107-020-01573-2

Nocetti M, Brunetti M, Bacher M (2015) Effect of moisture content on the flexural properties and dynamic modulus of elasticity of dimension chestnut timber. Eur J Wood Prod 73(1):51–60. https://doi.org/10.1007/s00107-014-0861-1

Nocetti M, Brunetti M, Bacher M (2016) Efficiency of the machine grading of chestnut structural timber: prediction of strength classes by dry and wet measurements. Mater Struct 49(11):4439–4450. https://doi.org/10.1617/s11527-016-0799-3

Olsson A, Pot G, Viguier J, Faydi Y, Oscarsson J (2018) Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce (Picea abies L.), Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and European oak (Quercus petraea (Matt.) Liebl./Quercus robur L.). Ann Forest Sci 75(4):33529. https://doi.org/10.1007/s13595-018-0781-z

Ravenshorst GJP (2015) Species independent strength grading of structural timber. Technische Universiteit Delft, Delft

Sandoz JL (1996) Ultrasoinc solid wood evaluation in industiral spplications. In: Proceedings of the 10th International Symposium on Nondestructive Testing of Wood, 26–28 September 1996, Lausanne, Switzerland

Unterwieser H, Schickhofer G (2011) Influence of moisture content of wood on sound velocity and dynamic MOE of natural frequency- and ultrasonic runtime measurement. Eur J Wood Prod 69(2):171–181. https://doi.org/10.1007/s00107-010-0417-y

Wang S-Y, Wang H-L (1999) Effects of moisture content and specific gravity on static bending properties and hardness of six wood species. J Wood Sci 45(2):127–133. https://doi.org/10.1007/BF01192329

Westermayr M, Stapel P, van de Kuilen JWG (2018) Tensile strength and stiffness of low quality beech (*Fagus sylvatica*) sawn timber. In: Proceedings of the World Conference on Timber Engineering 2018 (WCTE 2018), August 20–23, Seul, Republic of Korea

Woodcock DW, Shier AD (2002) Wood specific gravity and its radial variations: the many ways to make a tree. Trees 16(6):437–443. https://doi.org/10.1007/s00468-002-0173-7

V Paper V - Quality control for machine strength graded timber

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ORIGINAL

Quality control for machine strength graded timber

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Abstract The quality assurance of timber properties is important for the safety of timber structures. In the current study, the quality control options of timber are analysed for changing material quality under the prism of the different growth regions. Therefore, the control options—machine and output control in accordance with EN 14081—are simulated, and the performance is assessed and compared using 279,235 timber pieces from a production facility. For the data with only grading information available, the real properties were simulated based on 4158 specimens, for which destructive test results are also available. The results indicate that timber with desired material property values can be produced by both machine and output control. In direct comparison to machine control, the output control delivers timber which matches the requirements more frequently as quality shifts can be detected. Whenever lower timber quality is identified, the settings are increased. The output control system for multiple growth regions is not sensitive enough when the current attribute chart given in EN 14081-3 is used. With higher sampling rate the sensitivity can be increased. With the tested option—yield optimization—no additional yield improvement compared to machine control could be achieved.

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1 Introduction

For structural purposes the mechanical properties of timber, such as density, modulus of elasticity and strength, are of interest. These so-called characteristic values are defined in a strength class system that lists mean values or 5th percentiles of certain material properties for a population.

When grading, a piece of timber is assigned to a specific strength class based on boundary values, or machine settings in the case of machine strength grading, of certain grading properties. To ensure that these timber pieces reveal the actual timber properties, different methods are used. In Europe, the machine controlled method is widely used. The machine settings are determined on a large sample prior to the production process and remain constant during the entire production (Bengtsson et al. 2008). An alternative option defined in the European harmonised standard for graded structural timber EN 14081-1 (2011) is the output controlled method. Samples of the daily production are used to control the grading process. If quality deviations are registered, the machine settings will be adjusted. This method is suitable for grading limited timber sizes, species and grades or when individual settings for a certain raw material are required (Bengtsson et al. 2008).

Both machine and output control reveal difficulties associated with the high variability in the wood resource that can occur especially over multiple growth regions. Thus, machine control is not able to detect quality shifts as no monitoring of the output in terms of machine reading or destructive test is obligatory. Although output control is able to react to quality deviations, the system is not able to detect short-time quality variations (Sandomeer et al. 2007; Ziethén et al. 2010).

The growing demand for wood and wood products makes it of particular interest for sawmills to enlarge the

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pool of available resources and to produce timber from a larger number of countries. Due to the already mentioned higher variation in the timber properties associated, among others, with geographic propagation of timber specimens, the question arises whether the declared timber properties are achieved for timber originating from a larger number of countries, or a combination, so called “multiple growth regions”. This is of particular interest as such variation might limit the application of production control methods.

In the current study, both machine control and output control are applied to real production data for which the timber properties were simulated. The objective of the study is to estimate: (1) whether timber meeting the characteristic values can be produced with selected production control methods over multiple growth regions; and (2) whether some additional yield improvement can be achieved.

2 Materials and methods

2.1 Data basis

To assess the performance of different production control methods, the data of a real production facility have been used. The dataset used to assess the performance of different production control methods was provided by DOKA GmbH and includes the measurements of indicating properties—dynamic modulus of elasticity and density—recorded on 279,235 boards of Norway spruce (*Picea abies*) during the production. The measurements were done using Golden Eye 706 grading machine, which combines X-ray and vibration measurements for the prediction of grade determining properties (GDP).

For the 279,235 pieces of timber with missing grade determining properties, f_t (tensile strength) and E_t (modulus of elasticity in tension) were simulated. The simulation was carried out based on 4158 laboratory measurements of Norway spruce (*Picea abies*) from different projects performed at or in collaboration with Holzforschung München (HFM). A significant part of the data dates back to the GRADEWOOD project (Ranta-Maunus et al. 2011). The laboratory measurements include data from destructive tests in addition to the indicating properties that are also available in the production data set. The descriptive statistics and the coefficients of correlation of the grouped laboratory data are very close to the simulated ones and are therefore not presented separately in the following.

For the simulation, it was assumed that the relationship between the IP (E_{dyn} and ρ) and simulated GDP (f_t and E_t) in the production data set is equal to that of the laboratory data for a certain origin. The origin was defined as a combination of countries called a growth region and will be introduced later. Additionally, a log-normal probability distribution of tensile strength, dynamic and static moduli of elasticity was assumed. The simulation was performed in two steps. In the first step, the GDP with desired variance–covariance matrix were generated similar to Turk and Ranta-Maunus (2010). In the second step, due to the log-normal probability distribution of GDP, the heuristic optimization algorithm based on simulated annealing algorithm was applied to optimize the correlations. Using the heuristic approach of Charmpis and Panteli (2004) with a minor modification, the single board values were rearranged to increase the correlation coefficients to those observed in the laboratory data set. The elimination of the “uphill move”—the step in the algorithm which permits such rearrangements that decrease the coefficient of correlation to overcome local minima—allowed to reduce the computation time and optimize the correlation matrix. When nondestructively measured density and laboratory density are compared, the density measurements from the production dataset were considered as real density since $R^2 = 92\ \%$.

The descriptive statistics of indicating and simulated grade determining properties are presented in Table 1. It should be noted that the countries were assigned to the growth region based on geographic location and

Table 1 Descriptive statistics of manufacturing data set with simulated strength and stiffness

Growth region	Country	N	ρ (kg/m^3)		E_{dyn} (N/mm^2)		$E_{t,sim}$ (N/mm^2)		$f_{t,sim}$ (N/mm^2)	
			μ	CV (%)	μ	CV (%)	μ	CV (%)	μ	CV (%)
CEU	AT	38,264	447	10.6	11,809	18.6	11,022	21.2	28.7	37.4
	CZ	6786	471	9.6	13,177	15.5	12,276	18.0	31.9	33.1
	DE	19,623	445	9.4	11,225	17.0	10,446	19.9	27.1	36.3
EEU	RO	18,664	430	9.1	10,956	16.0	10,503	17.8	26.6	36.0
NEU	FI	28,581	470	8.5	12,984	14.6	11,690	19.2	31.2	33.4
	SE	42,159	490	9.3	13,811	15.7	12,434	20.1	33.3	33.9
	LV	73,736	468	10.3	13,567	16.2	12,234	20.4	32.7	34.1
	EE	51,422	466	10.2	13,565	16.1	12,228	20.3	32.8	33.8

comparable descriptive statistics. In the present study, the three growth regions Central Europe (CEU), Northern Europe (NEU) and Eastern Europe (EEU) are considered. The countries within the growth region show similar mean values and standard deviation of both E_{dyn} and ρ (density).

Furthermore, to take the differences in the growth regions into account, the relationship between the IP and GDP was assumed to be equal within a growth region and to differ between the growth regions. The most relevant relationship is the one which was used to assign timber pieces to strength classes: between the E_{dyn} and tensile strength ($f_{t,sim}$). For this the R^2 amounted to 61.4 % in CEU, 60.4 % in EEU and 52.3 % in NEU specimens.

2.2 Machine control

The machine controlled method was performed in accordance with EN 14081-2. The procedure includes the derivation of production settings for each sub-sample. The production settings were determined for the grading using only a single grading parameter—the dynamic modulus of elasticity (E_{dyn}).

For the determination of the initial settings a total sample of 1400 was taken from production dataset (n = 279,235). A sample of this size is usually used when initial machine settings for a combination of growth regions are determined. To cover all growth regions, 600 specimens out of 279,235 were sampled from CEU and 400 each from EEU and NEU. A larger sample was taken from CEU as a larger variation of timber properties is expected in that growth region. Each of these samples comprised several sub-samples coming from a specific country within a growth region. The specimens for the sub-sample were selected by taking systematically the first 200 specimens in a time series coming from the specific country.

The settings were derived for the combinations of tension strength classes (L-classes). The requirements for material properties of L-classes are listed in Table 2. Two class combinations L40–L25-rej and L30-rej were selected and tested for all control methods.

2.3 Output control

The data set with 279,235 specimens from the production facility with simulated strength and stiffness properties was used to simulate the output control and to assess its performance. Output control in accordance with EN 14081-3 (2005) and EN 14081-2 (2012) was simulated. In the following, only a brief overview is given.

Within the control procedure the mean MOE and 5th percentile of MOR are controlled. Density is not covered by the standardized control procedure. The procedure in the selected standards is specified for bending strength only and corresponding bending C-classes (EN 338 2009). However, for the current study the procedure was adapted to the tension strength L-classes used in accordance with EN 14081-4 (2009). Particularly the control parameters were adjusted to the ones of L-classes. The applied proof stress was calculated based on characteristic tension strength of the selected classes. As the output control in accordance with EN 14081-3 is of probabilistic nature, the output controlled system was repeated 100 times. The control procedure was repeated for the same production data using the specifications listed below. The initial settings for the output control remained the same for each simulation repeat.

2.3.1 Initial settings

The initial settings are established using the requirements for initial type testing for output controlled systems in EN 14081-2 (2012). The initial settings for grading were determined as in the case of machine control, using only the dynamic modulus of elasticity as grading parameter. First, the production settings were deduced from the same dataset of 1400 specimens which were used for the determination of machine controlled settings. The settings were estimated in such a way that all requirements for characteristic properties are fulfilled for the 1400 specimens. The number of specimens that would be used for initial settings for an output control system heavily depends on the available destructive test data at that time. In the case that a machine controlled system was in use before introducing output control, the data used for the derivation of machine controlled settings would probably also be used for the initial settings for output control. This approach was used as it also results in more robust settings from the start and allows comparing the different control systems from the beginning on.

Afterwards, the established settings were verified by applying a proof load on 60 specimens of each grade; they

Table 2 Required characteristic values of L-classes in accordance with EN 14081-4 (2009)

Grade	$f_{t,k}$ (N/mm^2)	$E_{0,mean}$ (N/mm^2)	$0.95{\cdot}E_{0,mean}$ (N/mm^2)	ρ_k (kg/m^3)
L40	26	14,000	13,300	420
L30	18	12,000	11,400	380
L25	14.5	11,000	10,450	350

were assigned to the grade using the established settings. The proof stress f_p is calculated from the characteristic tension strength ($f_{t,k}$) as given in EN 14081-2:

$$f_p = 0.96 \cdot f_{t,k}. \quad (1)$$

Applied stress and MOE are determined virtually for the proof loaded specimens. Out of the 60 specimens which were proof loaded, the total number of specimens that fail proof load is counted. For MOE, the mean of all 60 specimens is calculated. If the requirements for characteristic values (Table 2) are fulfilled, the settings will be "verified", otherwise rejected. If the settings are verified the production is started; if the settings are rejected, the settings are raised and the "verification" procedure is repeated.

2.3.2 Production control

During production, a quality control procedure is performed during each "new shift". Samples are taken and tested by applying a proof load to a specific level (Eq. 1). To control the process on a regular basis (the process remains "in control") in accordance with EN 14081-3 (2005), two samples of five specimens each are randomly selected for the daily control procedure. In order to test the effect of the sample size, the control procedure with only one sample of five specimens per shift in accordance with EN 14081-3 (2012) is also tested. For each sample, the number of specimens which fail the proof load and the mean modulus of elasticity of five specimens are recorded. These measurements are then used for the CUSUM control charts defined in EN14081-3 to control the timber quality over time.

The CUSUM procedure distinguishes between *attribute* and *variable chart*. The attribute chart is used to control the 5th percentile of strength. Thereby the number of specimens which fail the proof load (non-conforming units) is counted and controlled (Warren 1978). The variable chart is used to indicate the delay from the mean of the continuous variable. By using this chart type, the shift from the mean of the modulus of elasticity is controlled.

During the continuous process for both attribute and variable chart, the deviations of the measured values (non-conforming units and mean modulus elasticity) from the reference value (K) are calculated and the cumulative sum is tabulated (recorded in table) as in EN 14081-3 (2005). In the present study, the tabular calculation was substituted with equations which are at the background of the standardized procedure and were developed by Warren (1978). Both calculation procedures would lead to the same results. The cumulative sum for the attribute chart (2) and variable chart (3) is calculated using the following equations:

$$Sum_i = Sum_{i-1} + d_i - K_a, \quad (2)$$

$$Sum_i = Sum_{i-1} + K_v - E_{p,mean,i}, \quad (3)$$

where d_i is number of specimens which fail the proof load in the ith sample, $E_{p,mean}$ is the proof loaded mean modulus of elasticity in the ith sample, and K_a and K_v are CUSUM control constants for attribute and variable charts, respectively (Warren 1978). The values of control parameters for the attribute and variable charts—K, Y, Z—were selected as specified in EN 14081-3.

After the current *Sum* has been calculated, the decision rule is applied. This decision rule is based on comparison of the *Sum* with the predefined decision interval (Y). By exceeding the decision interval, the possible quality shift is noticed meaning that the system goes "out of control". So, if the sample fulfils the requirements of production control, the process will remain "in control" and specimens can be graded in the "new shift". Otherwise the "out of control" procedure is activated and further actions will be required in order to bring the system back "in control".

The actions to turn the process back "in control" are defined in EN 14081-3 and are: (1) confirmation test; (2) adjustment of the settings of 5 % or less; (3) adjustment of the settings of more than 5 %. The "confirmation test" is the additional test used to confirm whether the process is "in control" or "out of control", and the adjustments are the increase of settings and additional tests used to return the process back to "in control". Actions 1–3 were applied successively one after each other, when the system remained "out of control". So if the system detects "out of control" during the shift, first the "confirmation test" will be applied in order to confirm the quality shift ("out of control"). If after testing six samples (five specimens each) the system is indeed "out of control", further steps—settings adjustment—will be applied. In the present study, the settings are increased at first by moderate 2 % and six samples of five specimens each are tested with new settings. If the system does not turn back to "in control", the settings are further increased to 5 % overall compared to the initial settings of the current shift. It should be noted that such high adjustment would require the entire timber of the current shift to be re-graded.

Although all process steps, including re-grading, were applied strictly according to EN 14081-3, for evaluation purposes only both adjustment types (adjustment of the settings of ≤5 % and adjustment of >5 %) were summarized under the category "adjustments".

2.3.3 Yield optimization

For output control, reducing the settings to increase the yield is an optional step. Therefore, in the present study the output control is applied in two ways: one without settings reduction, denoted as output control in one direction and one with yield optimization, denoted as output control in two directions. Both differ only in the optional step—settings reduction. The settings are reduced in increments of 2 % compared to max. 5 % allowed according to EN 14081-3 and only after the new settings are "verified" by testing 12 sub-samples of five specimens each. As the rules for adjusting the setting are specified very poorly in EN 14081-3, adaptations have been carried out. When no signs of out of control within the last six shifts appeared, the settings were adjusted. Particularly, no specimens failed the proof load within the daily test samples, and the cumulative Sum of the variable chart does not exceed half of the CUSUM coefficient Y.

3 Results

3.1 Ungraded timber properties

The ungraded timber properties are observed on the basis of intervals (daily shift) for the entire data set in the same sequence of specimens as during the original processing in a production facility. The daily shift was set to 10,000 specimens that correspond to the daily average of specimens that ran though the production line. The observation is limited to the E_{dyn} used for the prediction of characteristic strength ($f_{t,sim,k}$), which is the critical material property for most grades in the current data set. The other properties—density and static modulus of elasticity—fulfil all the requirements of the specific classes after grading. For the current data set ρ of timber shows mean values above average.

For the ungraded timber in the current study, large variations in timber properties, such as E_{dyn} and $f_{t,sim,k}$, occur (Fig. 1). Despite of the variation the overall quality of the ungraded timber is high. The requirements of L25 for characteristic strength (14.5 N/mm^2) are almost met in minima of 5th percentile of tensile strength observed over time.

Between both the time series of E_{dyn} (Fig. 1a) and $f_{t,sim,k}$ (Fig. 1b) almost simultaneous peaks for the minima and maxima can be observed. Although the behaviour is almost identical in some periods, divergence in magnitude or even a small delay occurs. The variation in material properties over time is caused by the fact that for different growth regions different regression models are used to simulate the tensile strength. The relationship between E_{dyn} and f_t, varies over the selected growth regions. Additional uncertainty arises from the coefficient of determination between the dynamic modulus of elasticity and strength.

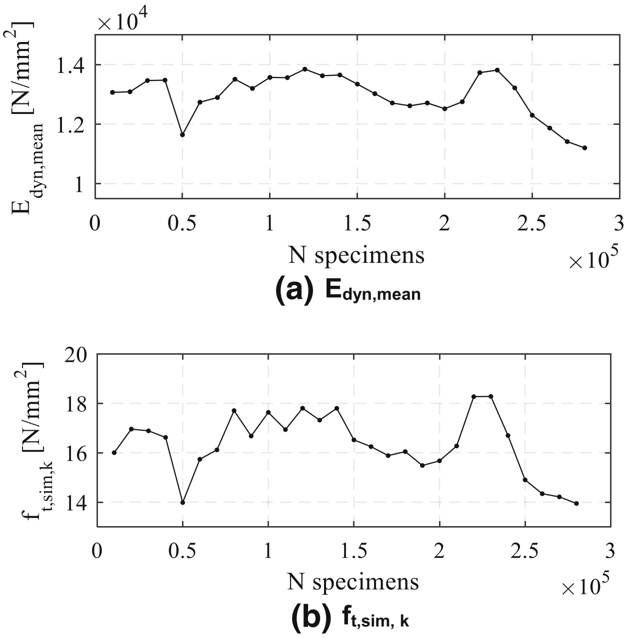


Fig. 1 Series of ungraded timber properties: **a** dynamic modulus of elasticity, **b** characteristic simulated strength

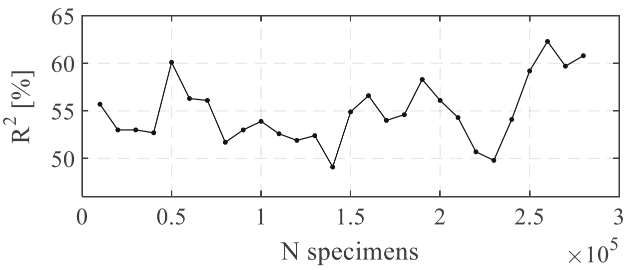


Fig. 2 Relationship between the indicating property E_{dyn} and timber strength (simulated) in time series

The difference in the models used as a basis for the simulation of the timber properties can be observed in the variation of the relationship between the E_{dyn} and $f_{t,sim}$ in Fig. 2. R^2 between E_{dyn} and $f_{t,sim}$ ranges between 50 and 62 %. The values of R^2 in the time series change in opposite direction to the ones of characteristic strength (Fig. 1b). So, the maxima of R^2 coincide with minima of both E_{dyn} and $f_{t,sim}$. These patterns within a time series can be compared to the descriptive characteristics of the "growth regions" (Table 1) as happened in these groups. For instance, timber from EEU (lowest mean $f_{t,sim}$, highest R^2) can be found at the end of the data set as well as at N = 50,000 specimens (see Fig. 1 and Fig. 2). In intervals where growth regions are mixed R^2 is lower.

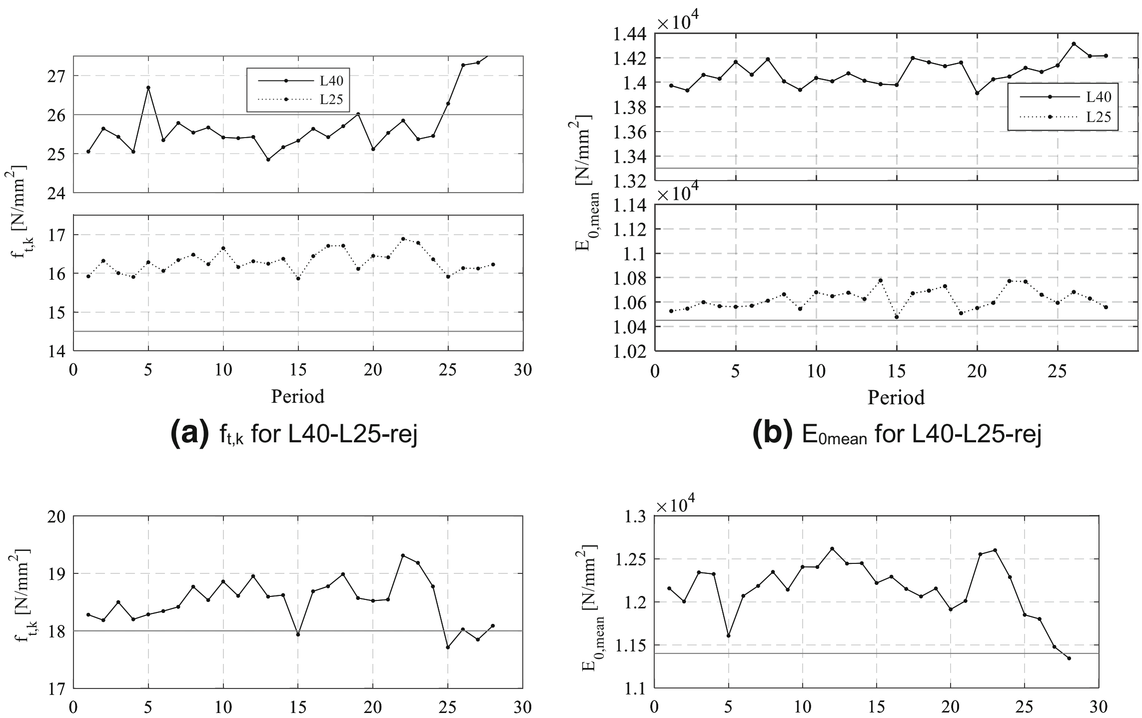
3.2 Machine control

In the present study, the possibility of using combined settings for three different growth regions was studied. The timber from every growth region was "virtually" graded using joint settings. The yield and performance of the machine controlled system will be introduced in comparison to output control in Sect. 3.4. In the following, machine control will be observed over the sequence of time. Each time interval accounts 10,000 of ungraded specimens. This number is considered as the daily average of specimen that runs through the production line within a shift.

Figure 3 illustrates the characteristic values over a time scale (per period) achieved by the machine controlled system when grading over multiple growth regions into grade combinations L40–L25-rej and L30-rej. ρ is not shown as it fulfils the requirements in all periods. The achieved characteristic properties vary within the time series for all grades. For L40, $f_{t,k}$ is below the requirements (26 N/mm^2) over a large number of periods in the time series, meaning that the settings do not fulfil the requirements. Only at the end of the time series, $f_{t,k}$ increases to the value above the requirements. For L40, $E_{0,mean}$ fluctuates around 14,000 N/mm^2 and is above the requirements (13,300 N/mm^2). For L25, the opposite tendency can be observed. $f_{t,k}$ for L25 is considerably above the required 14.5 N/mm^2, whereas $E_{0,mean}$ fluctuates very close around the required 10,450 N/mm^2. Nevertheless the requirements on $E_{0,mean}$ are met in each single period .

If the same timber pieces are graded to L30-rej, the characteristic values will be considerably better in comparison to the requirements (Fig. 3). For L30, the negative peak in $f_{t,k}$ can be observed at period No. 15 and at the end of the data set (Fig. 3c). The $E_{0,mean}$ values decrease at period No. 15 as well, however, the requirements on $E_{0,mean}$ are still met (Fig. 3d). At the end of the data set, both properties fall below the requirements. $f_{t,k}$ fluctuates close to the required characteristic strength value. For $E_{0,mean}$, this is only a single event. As for the selected settings, the characteristic values are achieved in almost every period; the settings are on the safe side.

The reason for the large number of periods below the characteristic values when grading to L40–L25, and conversely the small number of periods below the requirements for L30, is the sampling procedure. Although specimens were taken from every growth region, some more were sampled from Central (600 specimens) and Eastern Europe (400 specimens) compared to Northern Europe with only 400 specimens sample and at the same time far larger number of graded pieces. Overall, about 70 % of the 279,235 graded timber pieces originate from NEU and about 30 % from CEU and EEU only. The ungraded material from CEU and EEU showed lower mean values of characteristic properties and at the same time higher correlation with strength (R^2 CEU = 61.4 %, R^2 EEU = 60.4 % to R^2



(a) $f_{t,k}$ for L40-L25-rej
(b) E_{0mean} for L40-L25-rej
(c) $f_{t,k}$ for L30-rej
(d) E_{0mean} for L30- rej

Fig. 3 Time series of characteristic strength and stiffness for L40-L25-rej and L30 with period length of 10,000 sp. Machine controlled

NEU = 52.3 %). For the combined settings, the higher proportions of CEU and EEU shifted the initial settings for L40–L25 nearer to the optimum for these growth regions, particularly, to the lower settings for L40. Conversely, when grading to L30, the higher proportion of timber from CEU and EEU with lower tensile strength percentile values (Table 1) compared to NEU leads to higher settings–almost close to the ones optimal for these two growth regions. However, the 400 specimens from NEU with higher percentile lower the initial settings that would be proper for CEU and EEU during the combined settings derivation and lead to periods with unfulfilled requirements.

3.3 Output control

Compared to machine control the output control is characterised by the ability to adjust settings during the production. In the following, the reaction patterns of output control are presented with regard to the differences in timber quality when grading over multiple growth regions. The overall performance of output control is presented in comparison to machine control in Sect. 3.4.

3.3.1 Sensitivity of output control

For the output controlled system, the sensitivity towards low quality of incoming timber is essential. The results indicate that the system is capable of detecting initially too low machine settings both prior to the production and during the production.

First, the initial settings for L40 in grading class combination L40–L25 failed the verification procedure at the beginning of the production process. Therefore, the primary settings were subsequently increased by 2 %, and after the test failed for the second time the settings were increased by a further 3 % leading to an initial setting of 14,070 N/mm^2 (5 % increase in comparison to primarily deviated settings). If the settings for L40 were not raised by 5 % in 85.7 % of the periods, the characteristic values would not be fulfilled (Table 3). For L30 the estimated settings fulfilled all requirements of the initial type testing.

Second, the output controlled system is capable of detecting too low settings during the production. This issue is observed upon the occurrence of “out of control” procedures—confirmation tests and adjustments- and tested for each grading combination. As can be seen in Table 3, the number of periods show strength values $f_{t,sim,k}$ and $E_{0,mean}$ below the requirements if lower initial settings for L40 are used. 85.7 % of the periods do not reach 26.0 N/mm^2 and 13,300 for $E_{0,mean}$. For L30, the number of periods with characteristic values below the requirements is also high with 64.3 %.

The low settings (0.95 * $\text{Settings}_{\text{initial}}$) with a large number of periods below the requirements are detected with high frequency (Fig. 4). For the lower settings in comparison to the higher and normal ones, where the requirements are fulfilled almost in each case (Table 3), the number of additional tests and adjustments increases. Especially for L40 the number of adjustments is higher by a factor of ten.

Although the lower initial settings and thus lower quality can be detected using the output control, they are detected with low sensitivity. Such an issue can be observed in Table 4, where the frequency of confirmation test and adjustments over all 100 simulations for the above presented settings is shown. The settings are adjusted for L40 graded with lower initial settings more frequently compared with grading to L30-rej. One would expect the settings to increase 4.6 times per year, or every 2.6 months. It should be however noted that the additional tests (“confirmation tests”) occur more frequently. The expected occurrence of “confirmation test” amounts to 13.7 times a year for L30 with 5 % lower initial settings. This would lead to an increased frequency of additional tests—interval between tests of approx. 1 month—and therefore increased testing efforts. The frequency of confirmation tests is higher for L30 with 5 % lower initial settings than for L40 despite of the higher percentage of periods below the requirements for L40.

The difference between the occurrence of confirmation tests and adjustments as well as the overall low reactivity of output control is related to the control procedure and particularly to the chart type detecting the “out of control”. The output control distinguishes between attribute chart to control $f_{t,k}$ and variable chart to control $E_{0,mean}$. The chart types leading to the adjustments are depicted in Table 4. For L40 both confirmation test and adjustments are activated solely by the attribute chart, whereas for L25 with 5 % lower settings mainly by the variable chart. For L30 despite the lower number of periods below the requirements both variable and attribute charts lead to adjustments and thus cause the higher reactivity (higher frequency of adjustments) compared to L40. For cases where all requirements are fulfilled, only the attribute chart activates the “out of control” procedures.

The low reactivity of the attribute chart is related to the design of “output control” and particularly to the number of specimens which fail the proof load—the variable actually diagnosed by this chart type. As can be seen from Table 5, the number of “proof load failed specimens” is, as expected, the highest for the lowest settings. For L40 and L30 graded with 5 % lower settings, the percentage of specimens that failed under proof load (non-conforming units) is on average 4.7 and 4.3 %, respectively. This is above the acceptable quality level defined as 3 % of non-conforming units, which is accepted with 95 % probability. At the same time, the share of non-conforming units is still below the boundary of 19.5 % non-conforming units, defined as rejectable quality. The close distance of timber

Table 3 Percentage of periods where the requirements for L-grades are not fulfilled. For grading with initial settings of the output control system, without applying any control procedure, dependent on initial settings and grade combination

Grade (combination)	Periods (%)		
	$0.95 \cdot \text{Settings}_{\text{initial}}$	$1.00 \cdot \text{Settings}_{\text{initial}}$	$1.05 \cdot \text{Settings}_{\text{initial}}$
L40 (L40–L25-rej)	85.7	0.0	0.0
L25 (L40–L25-rej)	21.4	0.0	0.0
L30 (L30-rej)	64.3	17.9	0.0

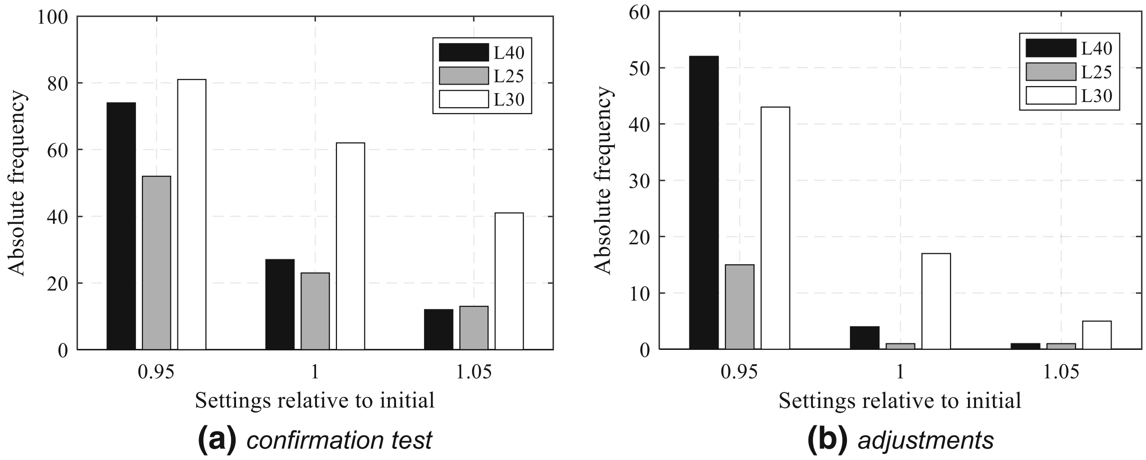


Fig. 4 Frequency of simulation repeats with "confirmation test" (**a**) and "adjustments" (**b**) for L40-L25 and L30

Table 4 Statistics of output control—frequency and chart types leading to adjustments—dependent on initial settings for 100 simulations

Grade (combination)	Settings	N of control procedures (times/year)		Chart type (%) (adjustments)		
		Conf.	Adj.	Attribute	Variable	Attr & Var
L40 (L40–L25-rej)	$0.95 \cdot \text{Settings}_{\text{initial}}$	10.0	4.6	100.0	0.0	0.0
	$1.00 \cdot \text{Settings}_{\text{initial}}$	3.3	0.4	100.0	0.0	0.0
	$1.05 \cdot \text{Settings}_{\text{initial}}$	1.3	0.1	100.0	0.0	0.0
L25 (L40–L25-rej)	$0.95 \cdot \text{Settings}_{\text{initial}}$	7.3	1.5	5.9	94.1	0.0
	$1.00 \cdot \text{Settings}_{\text{initial}}$	2.5	0.1	100.0	0.0	0.0
	$1.05 \cdot \text{Settings}_{\text{initial}}$	1.2	0.1	100.0	0.0	0.0
L30 (L30-rej)	$0.95 \cdot \text{Settings}_{\text{initial}}$	13.7	4.4	87.8	12.2	0.0
	$1.00 \cdot \text{Settings}_{\text{initial}}$	8.7	1.7	78.9	21.1	0.0
	$1.05 \cdot \text{Settings}_{\text{initial}}$	4.6	0.4	100.0	0.0	0.0

quality in terms of non-conforming units to the acceptable quality and the larger distance to rejectable quality level cause the low reactivity.

3.3.2 Sampling frequency

The effect of sampling frequency was analysed by simulating output control with different sample sizes. Furthermore, to check the sensitivity towards the timber quality, the output control was simulated with "normal" initial settings ($1.00 \cdot \text{Settings}_{\text{initial}}$) and 5 % lower initial settings.

Figure 5 shows the number of additional control procedures applied, such as confirmations tests and adjustments, if grading to L30-rej and L40–L25-rej with 5 % lower initial settings and different sample sizes of five specimens ("5") and two samples of 5 specimens each ("2 × 5"). By reducing the sample size to "5", the frequency of adjustments (Fig. 5b) is reduced by more than a half for L40 and L30. Thus, the settings are adjusted with low probability. For L25, the number of periods below the requirements is minor (Table 3) and as a consequence the difference between sampling rates is minor.

Table 5 Number of specimens which fail the proof load dependent on initial settings for 100 simulations

Grade (combination)	Settings	N specimens (%) μ ± SD
L40 (L40–L25-rej)	0.95 · $Settings_{initial}$	4.70 ± 1.02
	1.00 · $Settings_{initial}$	2.64 ± 0.71
	1.05 · $Settings_{initial}$	1.47 ± 0.45
L25 (L40–L25-rej)	0.95 · $Settings_{initial}$	1.51 ± 0.26
	1.00 · $Settings_{initial}$	1.25 ± 0.22
	1.05 · $Settings_{initial}$	1.09 ± 0.21
L30 (L30-rej)	0.95 · $Settings_{initial}$	4.33 ± 0.94
	1.00 · $Settings_{initial}$	3.35 ± 0.52
	1.05 · $Settings_{initial}$	2.47 ± 0.37

The effect of the reduced sampling frequency is observable if the data set is graded output controlled with "normal" initial settings. In this case, the requirements on the characteristic properties are not met only for L30 in 17.9 % of the periods. For L40 and L25, the requirements are met in each single period. The adjustments occur more frequently for "2 × 5" sampling size. One would expect the settings for L40 to be increased in 13 simulation repeats compared to 6 for a sample size "5". It needs to be taken into account that no settings adjustments occurred at all for L25 due to the high quality with lower number of specimens which would fail the proof load. In the case where the settings are fulfilled, two samples of 5 specimens each ("2 × 5") can lead to additional tests as well as false adjustments.

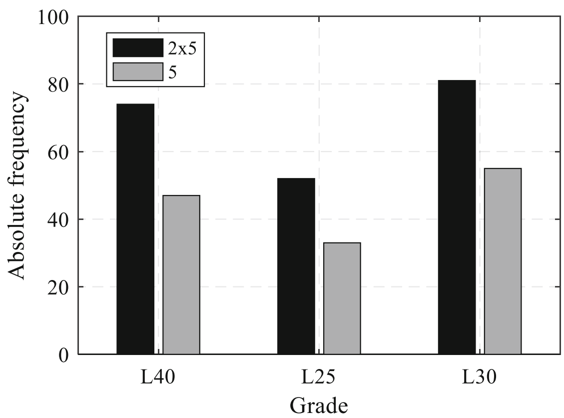
3.3.3 Yield optimization

As can be observed in Table 4, a low probability to adjusted settings exists, although no periods below the requirements occur (Table 3). For L40 and normal settings, the settings are unnecessarily adjusted on average 0.4 times a year, or in other words every 2.5 years. For 5 % higher settings even less frequent—0.1 times a year. In these cases, the yield decreases and the material properties of graded timber exceed the required values. Such an issue can be counteracted by the option to reduce settings specified in the European grading standard (EN 14081-3). By decreasing the settings, the yield can increase and the values of material properties decrease.

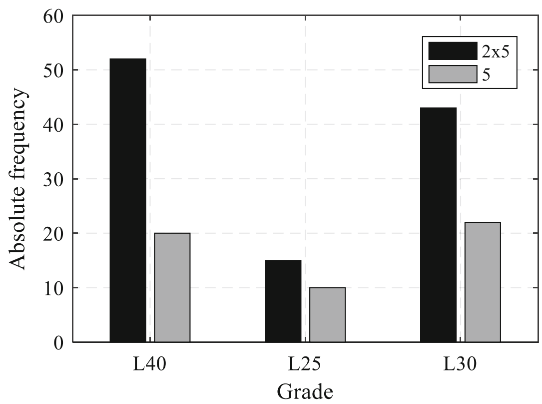
With an activated option to increase the yield in the present study the settings were subsequently decreased every 6th period if allowed by the output control routine. This is presented exemplarily for L40 in Fig. 6a. A clear reduction in the settings' mean value over 100 simulations occurs in characteristic steps. Due to the broad range of possibilities expressed as grey scaled polygon the settings can be decreased (min) as well as increased (max).

The overall implication of the settings on the characteristic strength is illustrated in Fig. 6b. As before, the grey scaled polygon shows the broad interval possible for the values of characteristic strength with minima (reduced settings) and maxima (increased settings) that can be reached. For L40, the mean per period remains above the requirements (26 N/mm^2). If the settings have recently been reduced (twice by 2 percent), a minima of as low as 25 N/mm^2 can be reached. Compared to the maximum line, which represents additional increase in settings that can occur by output control, the characteristic strength is reduced by approx. 2 N/mm^2 by chance. Hence, an overall broad range of possibilities exists.

The same patterns can be observed for L30. However, despite of the recent reduction (up to two times) L30 shows the lower difference between the minimal and maximal strength (up to 1 N/mm^2). The minimum is observed at the end of the data set at the same position as the minimum of $f_{t,k}$ of the machine controlled L30 in Fig. 3.

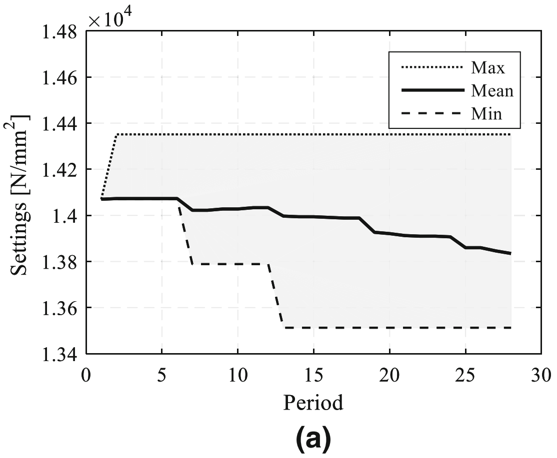


(a) *"confirmation test"*



(b) *"adjustment"*

Fig. 5 Frequency of simulation repeats where the "confirmation test" (**a**) and the "adjustment" (**b**) occur for the 5 % lower initial settings dependent on two five specimens sample ("2 × 5") and one five specimens sample ("5")



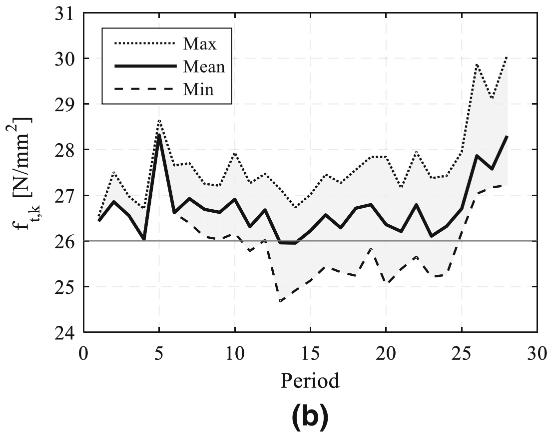


Fig. 6 Time series of settings (**a**) and characteristic strength (**b**) for L40 (L40-L25-rej) graded using the output control system with yield maximization

3.4 Machine vs. output control

The initial settings used for grading differed between the production control systems. The initial settings of the machine controlled system (MC) are below the settings of output controlled systems (OC), by approx. 5 % (Table 6). The settings for L40 were increased during the initial type testing as the proof load samples did not fulfil the requirements. On the other side, when grading to L30-rej the initial settings of machine control are slightly above those of output control.

Table 7 shows the ratio of reached characteristic values relative to the requirements for selected grades in the initial sample of 1400 specimens used to derive initial production settings presented above. For L40, if grading to L40–L25-rej using both machine and output control, the characteristic strength is the critical material property, which determines the grade. For L25 solely the $E_{0,mean}$ is a critical property. Other characteristic properties ($f_{t,k}$ and ρ_k) exceed the requirements by at least 10 %. For L30 both the characteristic properties $f_{t,k}$ and $E_{0,mean}$ are close to the requirements. In general, the values of output control are close to the requirements due to the simplified procedure of settings determination. However it should be noted that the values were achieved for L40 with 13,400 which could not be verified by initial type testing and as already mentioned raised by 5 %.

For the different production control systems applied, the achieved yield varies (Table 8). For grading combination L40–L25, the highest yield in the highest grade is achieved for machine control, which shows the lowest initial settings, whereas for L30 it was the output controlled system. For grading to L40–L25, even if the output control is applied with yield maximization, there is still a deficit in the yield amounting to more than 5 % compared to machine control. Although for L40–L25-rej the difference is remarkable, only small difference can be observed for grading to L30-rej. Considering the standard deviation which includes the reaction of output control, the yield in L30 can fall to the level achieved by machine control or can even increase (if the settings have been reduced recently). It is worse to note that the share of rejects changes only little, even if the output control with yield maximization is applied. As a consequence, the yield in the next higher grade (L25) is increased only slightly at the expense of rejects.

The higher yield in the highest grades for both grading combinations L40–L25-rej and L30-rej is achieved only by reducing the values of the timber properties compared to the required ones. Table 9 shows the number of periods where the requirements for selected classes are not matched. For L40, the machine control shows a very high percentage of periods below the requirements (78.6 %) compared to both output control in one and two directions. Especially for L40 output controlled in one direction in each single period all requirements are fulfilled. Even if the settings are reduced due to yield optimization (OC in two directions) the number of periods below the requirements is clearly lower compared to machine control. The decrease in periods below the requirements is likely to suggest the settings to be close to

Table 6 Initial settings (N/mm^2) for L40–L25-rej and L30-rej, dependent on the production control system

Grade	MC 1 rep	OC 100 reps	OC two directions 100 reps
L40 (L40–L25-rej)	13,600	14,070	14,070
L25 (L40–L25-rej)	9200	9250	9250
L30 (L30-rej)	9900	9800	9800

Table 7 Ratio of characteristic values reached for L40, L25 (L40–L25-rej) and L30 (L30-rej) to the requirements of L-grades in intial sample for settings derivation (1400 sp.). Machine vs. output control

Grade (combination)	Char property	MC	OC
L40 (L40–L25-rej)	$f_{t,k}$	1.019	1.012
	$E_{0,mean}$	1.046	1.037
	ρ_k	1.071	1.064
L25 (L40–L25-rej)	$f_{t,k}$	1.138	1.140
	$E_{0,mean}$	1.008	1.000
	ρ_k	1.094	1.094
L30 (L30-rej)	$f_{t,k}$	1.000	1.000
	$E_{0,mean}$	1.015	1.011
	ρ_k	1.037	1.034

Table 8 Yield (%) for L40–L25-rej and L30-rej, dependent on the production control system. Output control (OC) shows mean values and SD over 100 repetitions

Grade	MC 1 rep	OC 100 reps	OC two directions 100 reps
L40	38.4	31.1 ± 0.6	32.5 ± 1.7
L25	57.0	64.0 ± 0.6	63.3 ± 1.9
rej	4.6	4.9 ± 0.1	4.2 ± 0.5
L30	90.8	91.4 ± 0.5	91,9 ± 0.6
rej	9.2	8.6 ± 0.5	8.1 ± 0.6

Table 9 Percentage of the production periods in which the requirements on characteristic properties for each grade in combination L40–L25-rej and L30-rej are not fulfilled, dependent on the production control system. OC shows mean values and SD over 100 repetitions

Grade (combination)	MC 1 rep	OC 100 reps	OC two directions 100 reps
L40 (L40–L25-rej)	78.6	0.0 ± 0.0	11.4 ± 13.2
L25 (L40–L25-rej)	0.0	0.0 ± 0.0	0.5 ± 1.5
L30 (L30-rej)	14.3	16.9 ± 3.0	19.1 ± 2.6

optimal ones. For L30, the mean number of periods in which the requirements of L30 are not fulfilled appears to be similar for machine and output controlled systems. Among the mean values the machine controlled system with 14.3 % shows the lowest values and the output control in two directions the highest with 19.1 %. Considering the standard deviation, the output control in one direction can have the same or lower number of periods of non-fulfilled requirements. The minima, where all requirements are fulfilled, can be achieved by chance. The output control in two directions shows maxima with 28.6 %.

The difference in timber quality is observed more precisely in the histogram of characteristic strength values—the critical material property in both grading combinations—for the grades L40 and L30 in Figs. 7 and 8, respectively. Although for L30 only in 3 % of periods the requirements were also not fulfilled by $E_{0,mean}$, its distribution remained unchanged. For the machine controlled L40 the large number of periods below the required characteristic strength (26 N/mm^2) can be observed in a histogram (Fig. 7a). The peak of the strength is located between 25.2 and 25.6 N/mm^2. In comparison to machine control, no values below the requirements can be observed for output control (Fig. 7b). On the other side, periods with higher strength above 28 N/mm^2 or even 30 N/mm^2 occur. However, if the option to optimize the yield is activated (OC in two directions) for 19.1 % of periods the strength is below the required one (Fig. 7c). Fewer periods with higher strength in comparison to the one-sided output control also appear. It should be noted that the error bar shows that the frequency of periods below as well as above the characteristic strength can increase or fall by chance.

For L30, the low difference in yield and the number of periods below the requirements is reflected in the shape of the distributions (Fig. 8). All distributions show a similar shape. For the machine controlled system illustrated in Fig. 8a only a few periods fall marginally below the requirements (18 N/mm^2). For both output control systems, a few more periods observe minor values of characteristic strength (Fig. 8b, c). For the output control in two directions, for example, values with 1 N/mm^2 below the requirements can seldom be observed (Fig. 8c). The peak of machine control seems to be offset by the output controlled methods nearer to the required characteristic value.

4 Discussion

4.1 Machine control

Current research on machine controlled methods of production control is directed to establish whether the joint settings can be used for larger areas within Europe. The results of Stapel and van de Kuilen (2010) based on the bandwidth method indicated that for complex models with tensile strength, it is possible to grade with the same settings, irrespective of the growth region. In the present study, the possibility of using joint settings over multiple growth regions was examined on machine data for tensile strength. The grading was performed using E_{dyn} only, representing a rather basic grading machine.

The results clearly show that with E_{dyn} as indicating property grading over several growth regions is not optimal (Fig. 3). The initial sample for the derivation of settings is obviously not representative of all strength class combinations for the analysed population. For L40 graded in

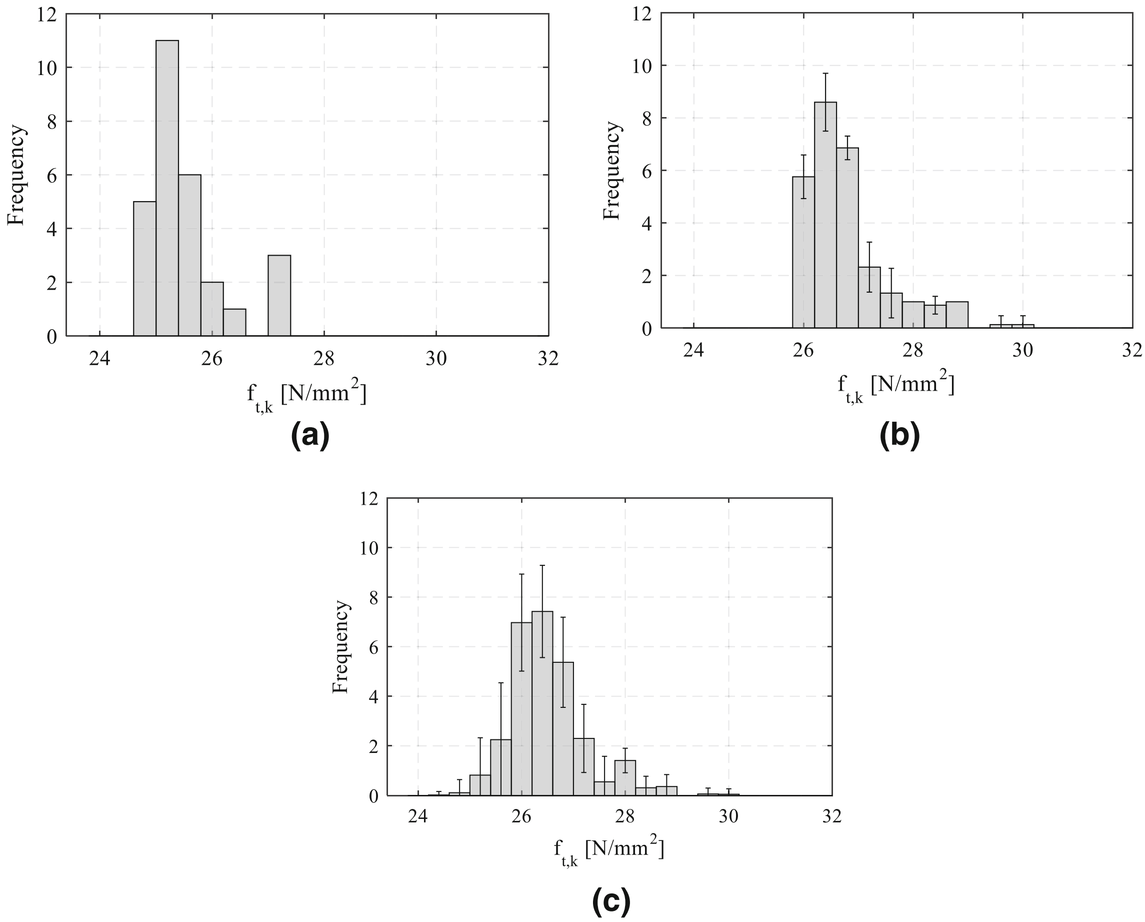


Fig. 7 Histogram of $f_{t,k}$ per period for L40 in combination with L40-L25-rej graded using: **a** machine control, **b** output control without yield maximization, **c** output control with yield maximization over multiple growth regions (*Error bar* indicates SD in the number of periods with certain $f_{t,k}$ values from the mean over 100 repetitions for OC)

combination L40–L25 the characteristic values were not fulfilled for 78.6 % of periods and strength values of as low as 24.8 N/mm^2 in comparison to the required 26 N/mm^2 were found. For L30, which was graded solely, the requirements on characteristic values were not matched in 14.3 % of all periods and the characteristic strength values were never far below the requirements. The higher percentage of periods below the requirements on characteristic values for L40 and conversely for L30 can be explained by the material selection for settings determination and differences in material properties between growth regions. As already mentioned for the combined settings the higher proportions of CEU and EEU shifted the initial settings for L40–L25-rej nearer to the optimum for these growth regions, particularly, to the lower settings for L40. On the contrary, the settings for L30-rej, were close to the optimal ones. The key factor was also that the specimens in the time series were not graded with the same composition of origins as in the sample for settings deviation.

The situation with too low settings is not unlikely to occur, as the initial settings are estimated on the representative sample for the whole geographical growth region and not for a raw material pool of a certain sawmill. Such a divergence should be taken into account in the estimation of the initial settings, especially as the material properties and relationships vary over the growth regions.

For the accuracy of the determined settings, representative sampling is an important issue. Usually, to determine the production settings in testing laboratories batches of timber from a limited number of origins are taken. The origin is most commonly a single saw mill. Determining the settings on a limited number of such origins includes bias compared to the random selection from the whole population. Although the random selection is desirable it is especially hard to achieve due to significantly high sampling efforts needed to cover the whole population at different times. In the present study, the sampling was done in batches of timber from a certain country taken at a certain time for the settings determination. Compared to a sample with random selection this could lead to less safe settings.

To overcome the problem of changing material properties, especially the relationship between modulus of

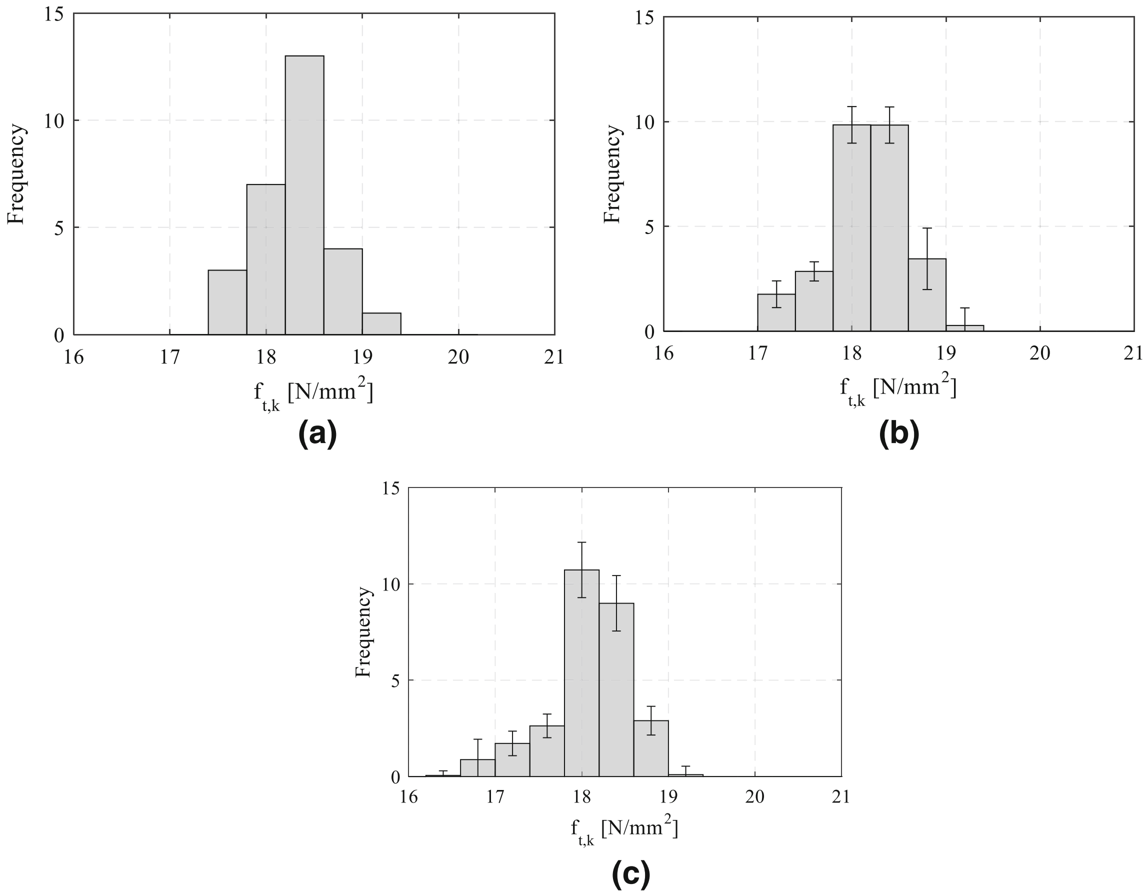


Fig. 8 Histogram of $f_{t,k}$ per period L30 in combination with (L30-rej) graded using **a** machine control, **b** output control without yield maximization, **c** output control with yield maximization over multiple growth regions (*Error bar* indicates SD in the number of periods with certain $f_{t,k}$ values from the mean over 100 repetitions for OC)

elasticity and strength, the most conservative settings should be selected for the grading process. As a consequence, properties of timber would be reliable for all considered growth regions. The possibility to extend the growth regions by using conservative settings has been mentioned by Ranta-Maunus et al. (2011). Thus, the conservative settings or individual settings for each growth region are the only options to grade using E_{dyn} as the only parameter. It can be assumed that by using complex models with knots and higher coefficients of determination better results as the ones suggested by Stapel and van de Kuilen (2010) would be possible.

4.2 Output control

The output control method and especially its limits have recently been studied. Such information, in reaction to quality shift, provides necessary insights into grading over multiple growth regions where the timber quality frequently changes. In comparison to previous studies on output control in accordance with EN 14081-3 by Bengtsson et al. (2008) and Ziethén et al. (2010), the present study examines the possibilities of using output control for multiple growth regions. The overall results indicate that for grading over multiple growth regions to L40–L25, the output control clearly shows better performance than the machine controlled system due to its ability to react. The success in this case is due to the feature to initially detect too low settings, which otherwise would lead to low quality of timber (unfulfilled requirements). Furthermore, the ability to react to too low settings during the production process exists (Fig. 4). This is in line with findings by Ziethén et al. (2010) who showed that output control can detect too low settings during the production. The increased reactivity clearly shows that the system seeks to maintain the required value of timber properties (strength and stiffness) by continuous adjustment of the settings. This is an important issue, as the timber characteristics can change over time due to, for example, timber supply.

Despite the advantages, several shortcomings of the output control method are evident. The results indicate the overall low sensitivity of output control towards quality shifts/too low settings. In case of L40, it would take on average 2.6 months if the strength requirements are not met in 85 % of the periods. This confirms previous results by Ziethén et al. (2010) and Sandomeer et al. (2008) that the sensitivity of output control is low. Thus, the low sensitivity of such adjustments shows that in the short run the quality of timber is not assured for each single period. However, over large time spans, where the settings are continuously adjusted when "out of control" is detected, the quality will fulfil the requirements.

The low sensitivity is caused by the attribute chart. In the present study, this type of control charts detects mainly the "out of control", as the characteristic strength is a critical characteristic property for higher grades. This chart type is admitted to detect quality shifts with a delay (e.g. Sandomeer et al. 2007). As stated by Shelley (1995), especially for small quality shifts from required quality, as in the present study, the quality shift is detected with a delay. Even for 5 % lower settings the number of specimens which would fail the proof load amounts in the worst case to on average 4.7 % for L40. This share is close to the defined acceptable quality level of 3 % non-conformities and is still far from 19.5 % of non-conforming specimens defined as rejectable quality level. Therefore, such timber with higher share of non-conforming units is not detected in each case.

Such shortcomings require reconsidering the entire output control approach. Without major revision, an increase in the sampling frequency seems to have some benefits. As shown in a present study, the use of double the sampling rate "2 × 5 specimens" compared to EN 14081-3 (2012) allows to increase the detection of output control and adjustments of settings if too low initial settings are selected. With the higher sampling rate more samples are taken from each single period and thus the probability to detect the low quality increases. However, one should consider that due to the probabilistic nature also the probability of "false alarm" and "false adjustments" increases leading to higher testing efforts. If for multiple growth regions the increased reactivity due to changing quality is an advantage, for other situations the trade-off based on cost of both alternatives should be made.

One essential issue of output control is the ability to reduce the settings in order to optimize the yield. The benefits of yield optimization have already been stated by Galligan and Devisser (2004). Although in the present study the yield optimization allowed to gain higher yield in higher classes only at the expense of periods with unmatched requirements, its importance could be observed. It allows to respond to/counteract the falsely increased settings ("false adjustments"), which occur even if all requirements are fulfilled (Fig. 4), or alternatively if initially too high settings are selected etc.

Although under the mentioned conditions for multiple growth regions the yield optimization is of an advantage, several aspects should be taken into account before reducing the settings. First of all, the adjustments require a certain (longer) observation period, as only information on the number of specimens which failed the proof load and $E_{0,mean}$ can be incorporated into the decision whether to adjust settings or not. Such information allows only indirect conclusions about characteristic strength values. Moreover, by observing the quality within a certain period of time the quality of timber currently graded is much likely not to be sufficiently incorporated; especially when the timber deviates only slightly from the required quality, as in the present study. Risks arise from the short time quality shifts, which are not unlikely, as can be seen from the current dataset.

The limited information on characteristic strength makes the efficient use of available information indispensable in order to avoid risks associated at least with timber currently graded. The application of modified, stricter (only two specimens can fail) decision rules in comparison to decision rules specified in the standard leads to a lower number of inappropriate adjustments and thus to a lower number of periods which do not fulfil the requirements. Thus, for the producer the number of subsequent additional tests is reduced and the consumer receives safer timber. However, this does not avoid the risk that can emerge due to the sudden quality change. To minimize the risk of adjustments at periods where low quality might occur, new sources of information are needed. Most promising would be the non-destructive information gathered during the production, such as for instance non-destructive CUSUM of ungraded timber proposed by Deublein et al. (2010): it would provide the producer with information about the current quality of ungraded timber, and clearly simplify the decision procedure.

It should be noted that the output control presented here is only a simulation. Assumptions concerning the initial settings were made in order to make the machine and output control comparable. So the initial settings for output control were determined on a sample of 1400 specimens. In practice, this would be the case where the data used for the derivation of machine controlled settings are available and can be used for the initial settings for output control. The destructive test data in this quantity (1400 specimens) is certainly not always available. The low availability of the destructive test data would lead to less robust settings and higher testing efforts during the production until the required quality level is reached.

Nevertheless, the implication of the initial settings for output control should not be overrated in practice. The output control, as discussed previously, is sensitive to too low settings. The verification of initial settings prior to the production is essential. Too low settings determined on a small sample still require verification. Even in the present study with 1400 specimens sample the initial settings for L40 did not pass the verification procedure. Only the increase of the primary settings allowed completing this procedure which is required for output control.

5 Conclusion

Timber can be produced safely using both machine and output controlled system. To produce timber safely using the *machine controlled* strength grading of timber *for multiple growth regions* with E_{dyn} as indicating property, conservative settings must be selected. The underlying problem is the different relationship between E_{dyn} and f_t among the growth regions.

The output control shows better performance—expressed in terms of periods with matched requirements—for L40–L25 due to its ability to react. In contrast, for L30 the machine controlled system was slightly better due to higher initial settings. However, the output control shows low sensitivity to quality shifts, which is connected to the overall low performance of the attribute chart. To counteract the low sensitivity of output control, a higher sampling rate is preferable if timber from multiple growth regions is graded. The general revision of output control is required.

The results of the comparison between machine and output controlled systems substantially depend on the initially derived settings for the machine controlled system. For the machine control, relatively low settings were used here. Hence, with output control no additional yield optimization in comparison to machine control could be achieved.

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References

Bengtsson C, Serrano E, Fonselius M, Riipola K (2008) Conformity assessment for machine graded timber by using output control. SP Rep 2008:01

Charmpis DC, Panteli PL (2004) A heuristic approach for the generation of multivariate random samples with specified marginal distributions and correlation matrix. Comput Statistics 19(2):283–300

Deublein M, Mauritz R, Köhler J (2010) Real-time quality evaluation of structural timber. In: Proceedings of 11th World Conference on Timber Engineering (WCTE 2010), Riva del Garda, Italy, ISBN: 978-88-901660-3-7

EN 14081-1 (2011) Timber structures—strength graded structural timber with rectangular cross section—part 1: General requirements. CEN European Committee for Standardization, Brussels

EN 14081-2 (2012) Timber structures—strength graded structural timber with rectangular cross section—part 2: Machine grading—additional requirements for initial type testing. CEN European Committee for Standardization, Brussels

EN 14081-3 (2005) Timber structures—strength graded structural timber with rectangular cross section—part 3: Machine grading—additional requirements for factory production control. CEN European Committee for Standardization, Brussels

EN 14081-3 (2012) Timber structures—strength graded structural timber with rectangular cross section—part 3: Machine grading—additional requirements for factory production control. CEN European Committee for Standardization, Brussels

EN 14081-4 (2009) Timber structures—strength graded structural timber with rectangular cross section—part 4: Machine grading—grading machine settings for machine controlled systems. CEN European Committee for Standardization, Brussels

EN 338 (2009) Structural timber—strength classes. CEN European Committee for Standardization, Brussels

Galligan W, Devisser D (2004) Machine grading procedures under the American Lumber Standard. In: Proceedings of 8th World Conference on Timber Engineering (WCTE 2004), Lathi, Finland

Ranta-Maunus A, Denzler JK, Stapel P (2011) Strength of European timber: Part 2. Properties of spruce and pine tested in Gradewood project, vol 179 of VTT Working Papers, VTT, Finland

Sandomeer M, Köhler J, Linsenmann P (2007) The efficient control of grading machine settings. CIB W18 paper 40-5-2, Bled, Slovenia

Sandomeer MK, Köhler J, Faber MH (2008) Probabilistic output control for structural timber: Fundamental model approach. CIB W18 paper 41-5-1, St. Andrews, Canada

Shelley B (1995) Lumber quality control with cusum—issues and considerations. Statistical process control technologies. State of the art for the forest products industry. In: Proceedings from the Statistical Process Control Conference, Forest Products Society, Madison,WI, pp 58–62

Stapel P, van de Kuilen JWG (2010) Growth areas in Europe with regard to different wood species and grading principles. Proceedings of 11th World Conference on Timber Engineering (WCTE 2010), Riva del Garda, Italy, ISBN: 978-88-901660-3-7

Turk G, Ranta-Maunus A (2010) Approach of dynamic production settings for machine strength grading. In: Proceedings of 11th World Conference on Timber Engineering (WCTE 2010), Riva del Garda, Italy, ISBN: 978-88-901660-3-7

Warren W (1978) Recent developments in statistical quality-control procedures for msr. In: Proceedings of 4th Nondestructive Testing of Wood Symposium, Vancouver, Canada

Ziethén R, Bengtsson C, Lycken A (2010) Machine strength grading—"output control" as a method for production control. In: Proceedings of 11th World Conference on Timber Engineering (WCTE 2010), Riva del Garda, Italy, ISBN: 978-88-901660-3-7

VI Paper VI - Analysis of economic feasibility of ash and maple lamella production for glued laminated timber

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Analysis of Economic Feasibility of Ash and Maple Lamella Production for Glued Laminated Timber

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Abstract: *Background and Objectives:* In the near future, in Europe a raised availability of hardwoods is expected. One possible sales market is the building sector, where medium dense European hardwoods could be used as load bearing elements. For the hardwood species beech, oak, and sweet chestnut technical building approvals already allow the production of hardwood glulam. For the species maple and ash this is not possible yet. This paper aims to evaluate the economic feasibility of glulam production from low dimension ash and maple timber from thinnings. Therefore, round wood qualities and the resulting lumber qualities are assessed and final as well as intermediate yields are calculated. *Materials and Methods:* 81 maple logs and 79 ash logs cut from trees from thinning operations in mixed (beech) forest stands were visually graded, cant sawn, and turned into strength-graded glulam lamellas. The volume yield of each production step was calculated. *Results:* The highest volume yield losses occur during milling of round wood (around 50%) and "presorting and planning" the dried lumber (56–60%). Strength grading is another key process in the production process. When grading according to DIN 4074-5 (2008), another 40–50% volume loss is reported, while combined visual and machine grading only produces 7–15% rejects. *Conclusions:* Yield raise potentials were identified especially in the production steps milling, presorting and planning and strength grading.

Keywords: volume yield; European hardwoods; low quality round wood; strength grading; glulam

1. Introduction

The share of hardwoods in the wood stock of Central European forests is steadily increasing [1]. The higher availability of hardwoods requires the development of new markets and new value chains for an overall increase in use. A possible, large sales market is the application in load-bearing structures.

Medium dense hardwoods have preferable mechanical properties compared to softwood. The higher tensile strength of hardwoods leads to either smaller member dimensions or higher load carrying capacities. The high bending strength for hardwood glulam (up to 48 MPa) has been reported by Blaß et al. [2] and Frühwald et al. [3] for beech glulam and by Van de Kuilen and Torno [4] for ash glulam. In recent years, a number of technical approvals for hardwood glulam have been issued:

Beech glulam [5],
VIGAM oak glulam [6],
Schiller oak glulam [7], and
SIEROLAM glulam of chestnut [8].

Despite the attractive mechanical properties, the use of hardwoods in structural applications remains minor. According to Frühwald et al. [3] and Mack [9], more than 90% of the glulam products in Europe are made of softwood (mainly spruce). The survey by Ohnesorge et al. [10] on glulam producers in Germany, Switzerland, and Austria revealed that in the year 2005 out of 900,000 m^3 of glued rod-shaped solid wood products only 1% contained hardwood.

A number of technological reasons as well as historical and silvicultural reasons has led to the fact that mainly softwood is used in wood construction. The use of softwood has been favored over decades because the physical properties are quite predictable and differences between the different softwood species are small. Furthermore, softwood is characterized by long, straight logs with low degrees of taper, homogeneous assortments, and few knots that are usually evenly distributed [11]. There are several further technological constraints for the use of hardwoods in structural applications, such as lack of knowledge of the long-term behavior of hardwood gluing, or the less number of certified grading machines compared to softwood, non-harmonized standardization and production processes not optimized for hardwood species.

One major aspect for the broader use of hardwoods in construction (especially glulam) is the economic feasibility of the production. For hardwoods, at present, no calculated data from a production facility is available. Torno et al. [12] estimated the production cost of ash lamellas to be three times higher as of spruce lamellas. Thus, besides the higher load-bearing capacity of hardwood glulam, the cost-efficient use of the resource hardwood is required, in order to reduce this cost difference. This includes both the optimization of the production process and of the resources used. Processing cheap, particularly small diameter hardwood logs, which are usually used for energy recovery in Europe [12], is one of the frequently discussed issues. Exploiting small diameter hardwoods for material utilization, e.g., sawing, is an important issue in Northern America as well [13].

It is the aim of this paper to contribute to the overall goal of an effective use of the available hardwood resources by minimizing the waste of each production step (of glulam lamellas) separately and for the entire production. The use of small diameter logs from thinnings as a poor-quality resource is the focus of this yield analysis. In the current study, the yield analysis from log sections to planed and graded glulam lamellas is performed using state of the art processing technology. Moreover, the achieved yields are linked to the mechanical properties relevant for glulam lamellas and measured for the investigated samples. Doing so, the economic feasibility of lamella production out of small diameter logs of the rare hardwood species maple and ash can be estimated. The single production steps and technologies of the production of glulam from low-dimension maple and ash logs are analyzed and described.

2. Conversion Efficiency of Hardwoods

In literature, different terms exist to measure the conversion efficiency. In Northern America, the recovery rates with measures like lumber overrun, lumber recovery factor (LRF) and cubic lumber recovery (CLR) are used. In Europe, the term yield is most commonly used. All these definitions have in common that they calculate the volume ratio between the output sawn product and the input logs. The term yield goes even beyond that and can be determined for each production step separately. It can include final, as well as intermediate, products. This allows revealing and analyzing the weakest points of the production process. The use of waste material as side product or for energy production can also be considered. A higher lumber volume does not necessarily lead to higher lumber value. That is why it is important to distinguish between lumber volume recovery and lumber value recovery. For sawmill owners or managers, the latter is decision relevant [14].

Due to the low production volumes of hardwood glulam, yield values are known to only a very small extent. Studies on European hardwoods analyzing the yield from log to planed (dry-dressed) lumber are rare. Torno et al. [12] performed an extensive study on the production of beech lamellas and Van de Kuilen and Torno [15] on beech and ash lamellas. For lamellas sorted according to the German visual grading standard DIN 4074-5 [16], volume yield values as high as 26% for beech and

27.7% for ash were attained. When sorting the lamellas according to the more stringent sorting rules of the German technical approval Z 9.1 679 [5], for the production of glulam the total yield starting at round wood (middle diameter classes 2b–6) ended at only 22% for beech and 26.9% for ash. In this case, however, higher mechanical properties are presumed. As shown by Torno et al. [12], the cutting pattern and the sawing technology affect the final yield. For graded beech lamellas those can drop to 10% or rise to 26%. The highest yield was attained with the grade sawing method, where a vertical bandsaw headrig cuts "around the log" until only a heart plank is left. In these studies, in addition to the cutting pattern and the sawing technology, the quality and the diameter of the round wood had a major influence on the final yield. Frühwald et al. [3] estimate the total yield of the production of high-quality beech glulam from good to medium round wood qualities (B and C) to be around 28.5%.

The reported final yields for hardwood lamellas are below the ones for softwoods. Final yields of the latter range from 24.5–38.5% [17,18]. Even higher yield values of 40% are stated by Torno et al. [12] for a modern spruce profiling unit. Frühwald et al. [3] mention that the final yield depends greatly on the size (production volume) of the glulam producing company. Only looking at the production of spruce glulam from dried sawn lumber, big producers are able to attain yields between 69% and 75%, while little glulam producers only reach yields of 53%.

Studies like the ones presented by Torno et al. [12] and Van de Kuilen and Torno [15] on the yield from logs to planed and strength graded hardwood lamellas are scarce. A few studies describe the yields of only individual production steps. Their results are summarized below.

2.1. *Sawing/Milling*

According to Steele [19], the following factors influence the lumber recovery in sawing (milling):

- Log diameter, length, taper, and quality
- Kerf width
- Sawing variation, rough green-lumber size, and size of dry-dressed lumber
- Product mix
- Decision making by sawmill personnel
- Condition and maintenance of mill equipment
- Sawing method

In the study of Lin et al. [14] in small US hardwood sawmills the factors log grade, diameter, sweep, length, species and sawmill specifications had a significant influence on the lumber volume recovery. It is also stressed that interactions between different factors can have a significant influence on the lumber volume recovery. Further influencing factors like board edging and trimming are also introduced. Richards et al. [20] simulate the volume and value yield of sawing hardwood lumber depending on the above mentioned factors. In their simulation the volume yield of live sawing is always higher than that of any four-sided sawing pattern (quadrant, cant, and decision), when sawing the same size logs. When sawing small logs with large core defects the value yield, though, is higher when applying a four-sided sawing pattern. The authors also emphasize the importance of the rotational position on the carriage for the first cut.

Ehlebracht [17] compares volume yield values of four German sawmills for the sawing of square-edged sawn lumber (rough green) from low dimension beech logs. The highest yield value of 57% is attained by a gang saw headrig utilizing the cant sawing method [20]. The lowest yield value of 36% is produced by a circular saw headrig, which produces a comparatively wide kerf. These values are consistent with the values reported by Emhardt and Pfingstag [21] and Fronius [22] that, when combining their findings, present values that range from 42–47% for the production of square-edged sawn lumber from low dimension beech logs (middle diameter classes 2b and 3a). The lower yield values of Ehlebracht [17] are comparable to the 35% yield reported by Fischer [23] for the production of parquet friezes and pallet boards from low dimension oak logs. For five small US hardwood mills, Lin et al. [14] report cubic recovery percentages (CRP) of 53.2% for red oak (*Quercus* *rubra*) and 57.5% for yellow polar (*Liriodendron tulipifera*). The CRP expresses the volume of rough green lumber as percentage of cubic log scale volume and is therefore comparable to the yield of the production step "sawing" analyzed by Ehlebracht [17]. The mean small-end diameter (SED) of the input logs in the study of Lin et al. [14] was 33 cm, i.e., also low dimension logs were sawn. All five sawmills used the grade sawing method—two with circular saw headrigs and three with bandsaw headrigs. The simulations of Richards et al. [20] for US hardwood mills result in volume yield values, which range from 54– 76%. The high values, though, are only attainable, when live sawing large logs. According to Fronius [22], a further yield drop of 15–20% (relative to the original round wood volume) is to be expected when square edging live sawn lumber.

2.2. Drying

Drying losses arise from volumetric shrinkage and the quality of the sawn lumber after drying. For hardwoods such as oak, improper drying results in staining, checking, splitting, and warp, which leads to a reduced sawn wood value [24,25]. Therefore, proper drying schedules are of high importance.

Generally, the higher the specific gravity of the wood is the higher is also the volumetric shrinkage [26]. It varies within a species and even for lumber from the same log. The volumetric shrinkage during technical drying of rough green lumber to a moisture content of 12% ranges from 14–21% for beech, from 12.8–13.6% for ash and from 11.5–11.8% for maple [17,27]. Spruce shrinkage losses are around 12% [27]. The volumetric shrinkage in the production of hardwood lamellas for glulam lies between 11% and 17% for beech and at 9.8% for ash [15].

2.3. Planing

Planing losses depend on the chosen oversize, the final product and the drying quality (i.e., warping and bowing). The resulting losses present a combination of planing away the oversize and sorting out (presorting) boards with intensive bowing. For example, when trimming the lamellas to shorter lengths, the oversize can be reduced and thus the planing losses are also reduced. In similar studies to the presented one [12,15], planing and presorting losses (due to bowing) for the production of hardwood glulam lamellas vary from 18–46%—a relatively wide range.

2.4. Grading

Grading is an important step within the production, as the quality of sawn wood is assessed in terms of appearance (i.e., cladding, furniture) or mechanical properties predicted. As a consequence, a discrete value is assigned to a lumber specimen. Both the quality of the produced lumber in terms of achieved mechanical properties and the yield are of interest. For grading, the yield is the share of dry-dressed lumber (dried, jointed, and planed), which is assigned to a certain quality class and not rejected.

Data on hardwood grading yield in general, and on strength grading in particular, is scarce, since hardwoods are rarely strength graded. Generally, the yield losses depend on the grading method (machine vs. visual grading), wood quality, growth region, cross-section, and sawing pattern selected. For European hardwoods, the effect the single mentioned factors have on the grading yield, are known to only a small extent. If lamellas are sawn pith free, the grading losses are lower compared to other sawing patterns. This is because the pith is a general rejection criterion for visually graded hardwood lumber after the German visual grading standard for structural timber DIN 4074-5 [16]. Thus, Glos and Torno [28] report for 324 ash boards and 459 maple boards graded according to DIN 4074-5 rules for joists rejection rates of as high as 21% and 37% due to pith and extreme grain deviation. It should be mentioned, though, that for that study the visual assessment of the boards is only being made for that part of each specimen, which is selected as free testing length. In Torno et al. [12] the loss values for beech lamellas range from 37–62%, if graded visually in accordance with the German visual grading rules for structural lumber DIN 4074-5 [16]. If lamellas are graded in accordance with the German technical building approval for beech glulam Z 9.1 679 [5] the rejection rate increases to 47% and 69%.

3. Test material

The round wood used for this investigation came from thinnings in mixed forest stands (mixed beech forests) of the state forestry offices Leinefelde and Heiligenstadt (Central Germany). The wood was harvested in the winter of 2014/2015 with harvester technology. Until the milling in June 2015, the round wood sections (logs) with a length between 3.20 and 3.40 m remained on the log yard of the department sawmill. According to the transport invoice 14.89 m^3 (79 logs) of ash (*Fraxinus excelsior* L.) and 16.25 m^3 (81 logs) of maple (80 logs of *Acer platanoides* L. and 1 log of *Acer pseudoplatanus L.*) were delivered (with bark). For the yield analysis, round wood sections (logs) with the following characteristics were ordered:

- Round wood quality C or worse (according to the Framework Agreement on Raw Timber Trade in Germany-RVR [29]);
- Length ≥ 3.20 m; and
- Round wood diameter classes 2–3

4. Production Steps and Determination of Characteristics

4.1. Round Wood Sections (Logs)

On the log yard the round wood sections were trimmed uniformly to a length of 3.15 m in order to be able to determine the heartwood coloring (i.e., brown heart) on both ends. At the top (small) end of each trunk a slice of 1–2 cm thickness was cut off. The final cut was performed at the bottom of each trunk (large end) to a length of 3.15 m. Thus, total log volumes were reduced to 14.3 m^3 for ash and 15.8 m^3 for maple. For each round wood section the minimum and the maximum diameter was determined in the middle of every 25 cm section. The last section only had a length of 15 cm. Using the mean diameter for each 25 cm section and the one 15 cm section (d_{Mn}), the section volumes were calculated with Huber's formula. The single section´s volumes were then added up resulting in Equation (1):

$$V_{Sec.} = \left(\sum_{1}^{12} \frac{\pi}{4} \times 0.25\ m \times d_{Mn}{}^2\right) + \frac{\pi}{4} \times 0.15\ m \times d_{Mn}{}^2\ \left[m^3\right] \tag{1}$$

The logs were sorted into diameter classes according to their small-end (top-end) diameter (SED) and into quality classes according to the specifications of the RVR [29] and DIN 1316-3 [30]. Both standards allow the assignment to classes from A (highest quality) to D (lowest quality). The quality-determining characteristics of the round wood sections were determined and recorded in accordance with Annex VIII (Measurement of the characteristics) of the RVR [29]. The characteristics shrinkage cracks, insect holes, tree cancer and the so-called moon ring (light discoloration in heartwood) were not recorded and thus were not part of sorting.

The RVR [29] offers no separate quality grading for maple and ash logs. Thus, depending on the particular characteristic, the oak grading rules (e.g., for knots, star shake, twigs, etc.) or those for beech (only for width of brown heart and heart shake) were used.

4.2. Sawing/Milling

The logs were milled with a mobile horizontal bandsaw headrig (Montana ME 90 2.0 from SERRA, Rimsting, Germany) with a kerf width of 2.45 mm. The cant sawing patterns used are shown in Figure 1.

The sawing patterns and the distribution of board dimensions were chosen for each log separately, mainly depending on the small-end log diameter (d_z or SED). Thus, the maximum yield could be attained. The pattern A was used most. If side boards were produced (colored boards in pattern C), they were edged to square edged lumber on a circular saw. For maple, five different lumber dimensions were sawn, for ash three (see Table 1).

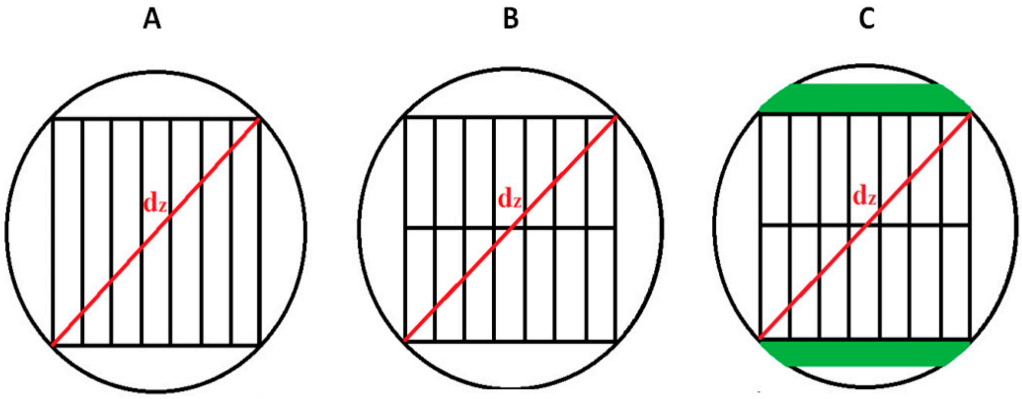

Figure 1. Cant sawing patterns of the milling.

Table 1. Nominal dimensions and quantities (*n*) of sawn green lumber and the resulting planed lamellas (dry-dressed lumber).

Sawn Green Lumber	Planed Lamellas	Maple	Ash
Width × height (mm) × (mm)	Width × height (mm) × (mm)	*n*	*n*
115 × 35	100 × 25	88	-
145 × 35	125 × 25	132	-
145 × 40	125 × 30	85	121
115 × 45	100 × 35	92	104
145 × 45	125 × 35	94	162

Only the main product glulam lamella was produced for this study. No side products, like trimming or baseboards, etc., were produced. The side products would raise the final yield. The final product—planed glulam lamellas—were subjected to destructive tensile testing after visual and machine strength grading (see sub sample "TH II" in Kovryga et al. [31]).

4.3. Drying

The technical drying took place in the in-house conventional dryer (HB Drying Systems, Almelo, The Netherlands). The drying parameters were chosen in order to ensure gentle drying of the boards. The drying process took 21 days. To determine the volumetric shrinkage, the dry lumber volume (at 12% moisture content) is subtracted from the sawn lumber (rough green) volume. For this purpose, for each dimension and wood species six lamellas were selected randomly. On these lamellas, the lengths (in mm) were determined with a tape measure on the rough green and the dry lumber. Lumber dimensions (in mm) were measured at intervals of 25 cm—starting and ending at the board ends.

4.4. Presorting and Planing

The dried boards were jointed and planed to glulam lamellas (dry-dressed lumber) with the nominal dimensions presented in Table 1. After the planing process, each lamella that could not attain the nominal dimension (cross-section) on the full length was sorted out (due to a combination of bowing and too little oversize). The volume of the remaining glulam lamellas was calculated by determining their lengths with a tape measure and using the nominal lamella dimensions.

4.5. Strength Grading of Planed Boards

4.5.1. Visual Strength Grading

To assess the quality of hardwood lamellas, different grading methods were used. First, each of the lamellas was visually classified according to the German visual strength grading standard DIN

4074-5 [16] over the entire length. The standard uses ten visual criteria to assign hardwood boards to visual strength grading classes. In the current study, the knottiness, presence of pith, bark inclusion, wane, and fiber deviation (grain angle) were considered.

All relevant grading criteria were measured as defined in DIN 4074-5 [16]. To assess the knottiness—one of the major parameters of strength grading—the criteria single knot (SK) and knot cluster (KC) were used. Single knot or *DIN Einzelast Brett (DEB)* relates the size of the single knot to the lamella width. For grading, the ratio (knot) with the highest value is indicative. Knot cluster (KC) or *DIN Astansammlung Brett (DAB)* is a multiple knot criterion, which considers all knots appearing in a (moving) window of 150 mm. Therefore, the spread of all knots over the 150 mm window is related to the width of the board. The edge knot criterion (E) or *Schmalseitenast* is an optional criterion for boards and represents the penetration depth of the knots appearing on the edge side only. A low value of these visual grading criteria stands for either rare occurrence or small size of the strength reducing knots and vice versa.

The only adjustment made concerns the measurement of the fiber deviation (grain angle). Fiber deviation is defined as an angle between the fibers and loading direction over a certain length and is measured in percent. The grain angle has a significant impact on strength [32]. Most grading standards indicate that the fiber deviation can be measured on drying checks or by the scribing method on the wood surface. Both methods are reported to have limited use for medium-dense hardwoods [33,34]. In the present study, the visible fiber deviation was detected on drying checks and, additionally, the surface was assessed qualitatively for fiber deviations exceeding the limits of DIN 4074-5 [16]. The specimens exceeding the limits are rejected.

Hardwood boards are assigned to the visual grades LS13 (highest quality), LS10 (medium quality) and LS7 (lowest quality) based on the boundary values listed in Table 2. To assign a lamella to a visual grade, all boundary values are to be met. Otherwise, the specimen is assigned to the next lower grade or rejected.

Table 2. Boundary values for grading of hardwood lamellas to visual grades (LS7 to LS13) after DIN 4074-5 [16].

	LS13	LS10	LS7
DEB (SK)	0.2	0.333	0.5
DAB (KC)	0.333	0.5	0.666
Edge knot (E)	-*	-*	-*
Pith	no	no	no
Fibre deviation	7%	12%	16%

* No requirements set.

Additionally, to estimate the effect of the grading parameters pith and DAB on the yield, two grading combinations—one without any requirements on pith and one without any requirements on pith and DAB—are applied to the lamellas.

4.5.2. Combined Visual and Machine Strength Grading

Additionally, the boards were graded using a combined visual and machine grading approach. The procedure was suggested by Frese and Blaß [35] and is used for beech glulam produced after the German technical building approval Z-9.1-679 [5]. This grading approach combines visual grading parameters (i.e., SK and KC) with the dynamic Modulus of Elasticity (MOE_{dyn}), a parameter used in most state of the art grading machines for softwoods. The MOE_{dyn} was determined using the "eigenfrequency" method (laboratory and grading machine ViSCAN by MiCROTEC, Bressanone/Brixen, Italy). In case of ViSCAN, the natural frequency (f) from longitudinal oscillation was combined with the density (ϱ) measured by an X-ray source, and the length (l) of the measured specimen (Equation (2)).

In the laboratory, the density was determined using the gravimetric method. Both measurements provide comparable results in terms of R^2 value (0.972).

$$MOE_{dyn} = 4 \times l^2 \times \rho \times f^2 \times 10^6 \tag{2}$$

The combined approach uses separate boundary values for visual grading parameters (i.e., SK, KC) and MOE_{dyn}. The boundaries presented by Frese and Blaß [35] are fitted to beech lamellas. For the present study, the combined grading is optimized for ash and maple and presented by the paper Kovryga et al. [31]. Table 3 shows the combination of boundary values selected for the current study. As example, for maple the "Solution B" and for ash the "Solution C" proposed for combined grading by Kovryga et al. [31] is selected. The presented combination allows grading to three different grades plus reject group. The highest grade shows characteristic tensile strength values (above 38 N/mm^2) fitting the tensile strength of finger jointed lamellas stated by Van de Kuilen and Torno [4].

Table 3. Optimized grading rules for combined visual and machine strength grading of ash and maple (according to Kovryga et al. [31]; maple: "Solution B", ash: "Solution C").

	Grade	Boundary Values					Resulting Tensile-Classes
		DEB (SK) (–)	DAB (KC) (–)	Edge knot (E) (–)	Pith (–)	MOE_{dyn} (kN/mm^2)	
Maple	**1**	0.1	0.1	-*	Allowed	13.9	DT38
	2	0.2	0.5	-*	Allowed	12.2	DT25
	3	0.3	0.6	-*	Allowed	10.9	T15
	Reject						
Ash	**1**	0.2	0.2	-*	Allowed	16.5	DT38
	2	0.3	0.3	-*	Allowed	15.5	DT34
	3	0.4	0.4	-*	Allowed	11.6	DT22
	Reject						

* No requirements set.

4.6. Yield Calculation

For the determination of the total yield, the yields of each single production step are added up. The yield of each production step is calculated by dividing the output product volume by the input volume. How volumes of each intermediate product are calculated and what assumptions are made for these calculations is described above for each production step separately.

5. Results and Discussion

5.1. Grading of Logs

Table 4 shows the sorting of the maple and ash logs into diameter and quality classes. Following the descriptions of Van de Kuilen and Torno [15], the diameter sorting was carried out by considering the small-end diameter (SED) inside bark. The supplied round wood sections mainly cover the diameter classes from 2a to 3b, with individual sections with diameters below 20 cm and over 40 cm. For maple and ash, the bark shows a mean thickness of 0.5 cm. Maple shows a higher number of logs graded to the higher quality classes (B and C) compared to ash.

Table 4. Number of logs per species sorted after small-end diameter (inside bark) class and quality class according to RVR [29].

Diameter Class		**2a**	**2b**	**3b**	**4**	**1b**	**2a**	**2b**	**3a**	**3b**	**1b**	**2a**	**2b**	**3a**	**3b**
Quality Class		**B**				**C**					**D**				
Quantity	**Maple**		3	2	1	4	18	11	9	3	5	14	5	2	3
	Ash	1					8	16	5	1	2	23	19	4	

Tables 5 and 6 show the results of the log quality sorting according to RVR [29] and DIN 1316 3 [30] in detail.

Table 5. Yields in % for quality sorting of logs according to RVR [29] separated after sorting criteria (log characteristics).

Log Characteristics	Maple				Ash			
	A	B	C	D	A	B	C	D
Callused knot (bump)	23	1	76		46		54	
Healthy knot	63	29	9		89	10	1	
Decayed knot	63	31	5	1	89	6	5	
Twigs	76	24			100			
Bump on group of broken of twigs	95	1	4		100			
Star shake/check	60	29	11		4	14	80	3
Heart shake/check	33	61	5	1	81	15	1	3
Frost crack	98		3		99		1	
Ring shake	98	3			99		1	
Bow (Sweep and crook)	48	14	6	33	38	1	5	56
Spiral (twisted) grain	98		3		100			
Rot	99			1	97			3
Log length	99		1		96		4	
Width of brown heart	86	14			25	46	29	
Final quality class of logs		8	56	36		1	38	61

Table 6. Yields in % for quality sorting of logs according to DIN 1316-3 [30] separated after sorting criteria (log characteristics).

Log characteristics	Maple				Ash			
	A	B	C	D	A	B	C	D
Length	99		1		96		4	
Mid-diameter	14	11	70	5		4	9*	
Callused knot (bump)	25		34	41	47		42	11
Healthy knot	95		5		91	3	6	
Decayed knot	90		8	3	96		4	
Eccentricity of pith	88	13			80	20		
Star shake/check	60		5	35	4			96
Heart shake/check	40	14	46		87	4	9	
Brown heart	66		34		38	25	37	
Bow (Sweep and crook)	61	5	1	33	39	5		56
Rot	99			1	97			3
Final quality class of logs	**1**	**1**	**26**	**71**			**4**	**96**

Tables 5 and 6 present the final assignment of the round wood sections into the quality classes (the last row of both tables) based on the individual class assignment for each sorting criterion. Each single criterion's influence on the grading can be seen as well as the total distribution of quality classes per species. For example, according to DIN 1316-3 [30], 71% of the maple logs are graded into the lowest quality class D (see Table 6). The final percentage value is a result of all wood characteristics combined. It can be seen that for maple the grading into the D class is mainly due to the characteristics callused knot, star shake, and bow. When sorting according to the RVR [29] specifications, mainly log bowing is decisive for sorting into class D (see Table 5). Especially in the second lowest grade C, it is observable that the two different quality sorting schemes weigh the different characteristics differently, i.e., have different characteristic's boundary values for the same class. While grading into RVR class C of maple is mainly due to callused knots (76%), DIN 1316-3 [30] sorting into class C is due to a number of characteristics (mid diameter, callused knots, heart shake, and brown heart). Both grading schemes sort the majority of the studied logs into the classes C and D.

In general, the two sorting guidelines for round wood use different lists of characteristics. For example, Table 6 shows that in the case of sorting according to DIN 1316-3 [30] the criterion mid-diameter leads to a classification into quality class C for 70% of the maple logs and for 96% of the ash logs. Compared to that, the diameter of the logs is not relevant, when sorting according to RVR [29]. The possible advantage of the absence of log size criteria is that the actual visible log quality can be assessed and used to qualify the logs for the production in addition to the diameter.

Looking at Tables 5 and 6, it also becomes obvious that—under the same storage conditions—ash logs tend to form more severe end cracks (star and heart shake) than maple. This cracking results in a serious deterioration of quality and leads to a reduced sawn lumber yield (mainly value yield). Thus, it is recommended to saw (mill) ash logs shortly after logging or adapt storage (e.g., water storage) to ensure the best possible lumber quality and highest yield. Short storage times' respectively adjusted storage conditions are also advised for maple logs, since fungal discoloration starting from the log ends presents problems [27]. For an end use as construction material, though, these discolorations may be of low significance, since they do not affect the elasto-mechanic properties of the lumber.

5.2. Yields from Logs to Unsorted Glulam Lamellas

Table 7 summarizes the volume losses and the resulting yields for each production step. It can be seen that the major production losses arise from sawing the logs and presorting the dried boards. Both species do not differ considerably.

Table 7. Yield for each production step from logs to planed lamellas (unsorted).

Product	Production Step (PS)	Maple				Ash			
		Yield		Waste/Loss		Yield		Waste/Loss	
		in m^3	in %	in m^3	in % PS	in m^3	in %	in m^3	in % PS
Logs		15.8				14.3			
	Milling/sawing			7.6	48.2			7.1	49.5
Boards (green)		8.2	51.8			7.2	50.5		
	Drying			0.7	8.7			0.8	10.7
Boards (dry)		7.5	47.3			6.5	45.1		
	Presorting & planing			4.2	56.3			3.8	59.6
Planed lamellas		3.3	20.9			2.6	18.2		

5.2.1. Sawing/Milling

The mean volume yield of sawing the 81 maple logs by the cant sawing method to square-edged lumber is 51.8%. The mean volume yield of sawing the 79 ash logs is with 50.5% slightly lower. The log diameter strongly influences the volume yield of this production step. The effect the mid-diameter has on the sawing yield of this study can be observed in Figure 2.

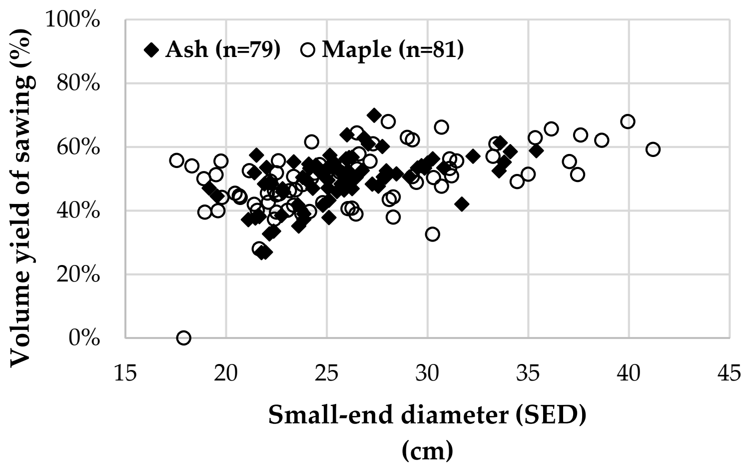

Figure 2. Volume yield of sawing ash and maple depending on the small-end log diameter (inside bark).

The higher the log diameter gets, the higher the yield gets. The variation in sawing yield values drops with increasing diameters, as the influence of the log grade (quality class) on the yield decreases. Compared to the log diameter, the quality class only has a minor influence. Wade et al. [36] analyzed data from 35 US hardwood mills and also concluded that a positive linear relationship between log diameter and sawing yield (in their case LRF) exists. In the simulation of Richards et al. [20] hardwood sawing yields of sawing low dimension logs (SED = 25 cm) by the cant sawing method start at 56.1%, while from logs with large diameters (SED = 71 cm) up to 67.2% rough green lumber can be produced. In Ehlebracht [17] only one of four hardwood mills attained a sawing yield of 57%, when cant sawing low-dimensional hardwood logs. Two mills achieved yields like this study (50% and 51%), while a mill with a circular saw headrig only reached 36% volume yield. All presented studies show that it is economically advantageous to sort out logs with diameters below a certain value. The boundary value for the diameter has to be determined for each production site and product separately. The results of Wiedenbeck et al. [13] give rise to the assumption that this boundary value also depends on the wood species sawn.

Lin et al. [14] prove that the log grade (quality class) has an effect on the hardwood volume recovery. In this study, this is only observed in the lower log diameter classes. The individual characteristics eccentricity of pith, ovality and taper show no significant influence on the yield of the first production step. The two latter characteristics are not part of the RVR [29] and DIN 1316-3 [30] sorting standards. Nonetheless, their influence on the yield during production is examined. For ash, the degree of bowing (in one direction) has no influence on the yield of milling. For maple, increased bowing (in one direction) leads to a decreased yield of milling. Multiple bows in one log (in one or more directions) decrease the yield of milling significantly. Comparing logs with one bow in only one direction with logs with multiple bows, the yield is reduced from 52.7 to 43.7% for maple and from 51.7 to 46.1% for ash. The same relationship—but less pronounced—can be found in so-called butt-cuts. In these first logs of trees taken above the stump, the milling process removes a high volume of wood from the large end of the log.

5.2.2. Drying

Drying of the green lumber was carried out for all dimensions and species with the same slow drying program, in order to avoid damages due to inadequate (i.e., too fast) drying. For maple, the volumetric shrinkage lies between 8.0% and 8.9% (average 8.7%), while for ash it lies between 9.6% and 11% (average 10.7%). For both species, these values lie in the lower range of the above-mentioned literature values. In some cases, the boards started warping (bowing, crooking, cupping, twisting, etc.) immediately after or even during the milling due to inherent tension in the trunks (eccentric pith, reaction wood, around big knots, etc.). Nonetheless, these boards were stacked and underwent drying.

5.2.3. Presorting and Planing

Before planing the dried boards, they were pre-sorted. Boards with extreme bowing were sorted out. If the infeed and outfeed rollers of the planer were able to press down the bow, resulting in fully planed board surfaces, the lamellas were not sorted out. Nevertheless, the volume loss of this production step is 56.3% for maple and 59.6% for ash. The resulting total yields of planed boards (unsorted glulam lamellas) are, thus, 20.9% for maple and 18.2% for ash. If the presorting was excluded from this calculation, i.e., if the bows were cut out (resulting in shorter lamella lengths) and thus all boards could be planed to the nominal dimensions, total yield values of 33.4% (maple) and 33.2% (ash) could be obtained. For future investigations, it is planned to evaluate the influence round wood quality has on presorting and planning losses. Especially for low-dimension logs of poor quality the question arises, how much of the resulting twisting and bowing in the dried lumber is due to the drying process and how much is already present in the rough green lumber.

5.3. Strength Grading of Glulam Lamellas (Planed Boards)

5.3.1. Grading Results

As explained in Section 4.5, the planed boards were graded visually according to the German visual strength grading standard DIN 4074-5 [16]. Furthermore, the result of two adjusted grading schemes were compared—when the criterion "pith" is excluded from visual strength grading according to DIN 4074-5 [16] and when only single knots (DEB) are evaluated according to DIN 4074-5 [16]. Additionally, the lamellas were graded following the combined visual and machine grading proposed by Kovryga et al. [31] and presented in Table 3.

Figure 3 shows the grading results for ash and maple, respectively. The second box of each diagram gives the results of visual grading according to DIN 4074-5 [16]. For both ash and maple, only few boards are sorted into the classes LS7 and LS10. The majority is either sorted into the highest quality class LS13 or rejected. When excluding the criterion pith from DIN 4074-5 [16] sorting (see third box), no ash lamellas and four maple lamellas were rejected. The majority of the lamellas is graded into LS13 (ash: 195; maple: 238). Only applying the DIN 4074-5 [16] boundary values for the criterion DEB (single knot) gives almost identical sorting results. The combined grading proposed and optimized by Kovryga et al. [31] for the here studied lamellas result in a relatively even distribution of lamellas over the three grades. For ash 6.8% and for maple 15.7% of the lamellas are rejected.

For grading according to DIN 4074-5 [16], a high effect of the pith criterion on the grade class assignment can be stated. Grading with pith as rejection criterion results in a reject rate of 48% for the ash boards and 38% for the maple boards. If the pith criterion is excluded from grading, none of the ash boards and only 1% of the maple boards are rejected. Similar results are reported by Torno et al. [12], who detected pith in 26% and 30% of the graded beech boards. Here the sawing pattern was similar to this study, but logs with larger diameters were sawn. Van de Kuilen and Torno [15] calculated for their study the ratio of pith containing board volume to initial round wood volume (inside bark) to be 0.2% for ash and 0.9% for beech. In this study, this ratio is 9.1% for ash and 8.0% for maple. This much higher appearance of pith can be explained by the fact that lower dimension logs were sawn and the overall log quality was poorer. Furthermore, the study of Van de Kuilen and Torno [15] used a special sawing pattern ("sawing around the log" or "grade sawing") designed to produce boards without pith. Generally, it can be concluded that the sawing pattern and the low log dimensions chosen for this study resulted in a high amount of pith boards, which have to be sorted out, when sorting according to DIN 4074-5 [16]. Pith is also the main downgrading criterion in the grading of ash and maple lamellas studied by Glos and Torno [28]. The rest of the boards of this study show good quality for both species, resulting in a high proportion in LS13 grading.

One explanation for the higher amount of pith containing boards in the ash compared to the maple collective can be the fact that in ash trees the pith is typically "wandering", which is due to crooked growth in early years [17,37]. Other reasons can be more severe bowing of the ash logs or littler log dimensions. Figure 4 proves that the small-end diameters are not severely different for the 81 maple and 79 ash log sections.

The bowing of the raw material was according to RVR [29] specifications only measured for log sections that had one bow over the entire log length. This criterion shows now difference between the species ash and maple as well (see Figure 4). Checking the number of logs with compound bowing (bowing into two or more directions) reveals a different picture, though. While only 55% of the maple log sections are characterized by compound bowing, 77% of the ash log sections have compound bows. This could be an explanation for the higher amount of pith containing boards in the ash collective. Since the collected data does not contain information on the degree of compound bowing, one cannot distinguish between the influence of the "wandering pith" and the log section bowing.

To finalize the discussion of the effect of the grading parameters on the yield, the effect of the knot cluster criterion (DAB) is observed. Comparing both visual grading options—for DIN 4074-5 [16] "without considering pith" and "only DEB (without considering pith and DAB)"—little to no changes can be observed (see Figure 3). The added value (information) of DAB for grading is illustrated in Figure 5, which plots the maximum DEB against maximum DAB values for all ash and maple boards. The paired values (boards) on the bisector show those boards, where the maximum DEB is bigger than or equal to any found DAB. For all other boards a DAB greater then the DEB is reported. The grey area indicates those boards, for which the criterion DAB leads to a sorting class downgrading, when sorting according to for DIN 4074-5 [16]. This is the case for only twelve maple boards (3.7%) and three ash boards (1.4%). Therefore, the criterion knot cluster (DAB) is not decisive for downgrading into a lower sorting class, if graded after DIN 4074-5 [16].

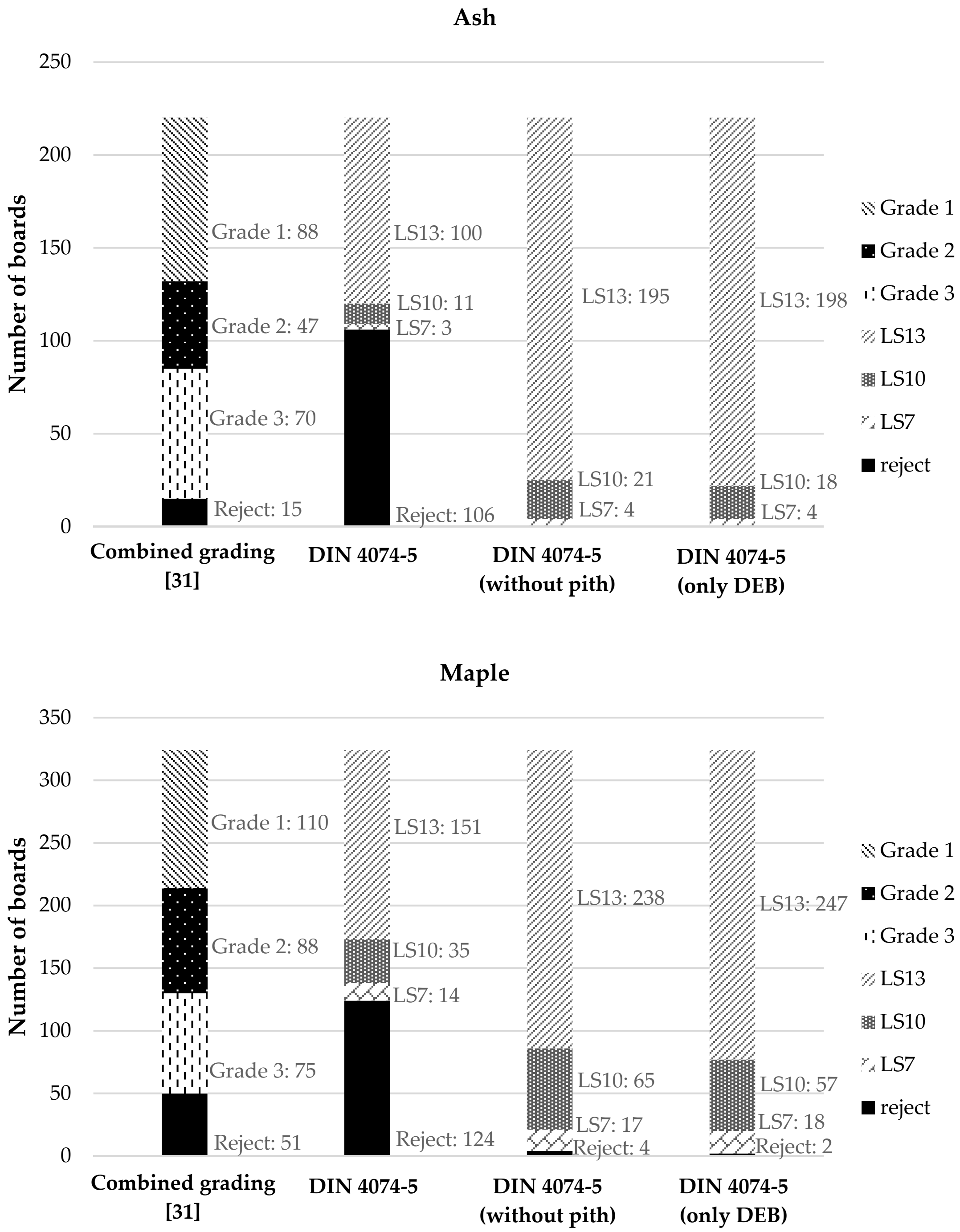

Figure 3. Yields for the combined (left bar) and visual grading (three right bars) of the planed ash and maple boards.

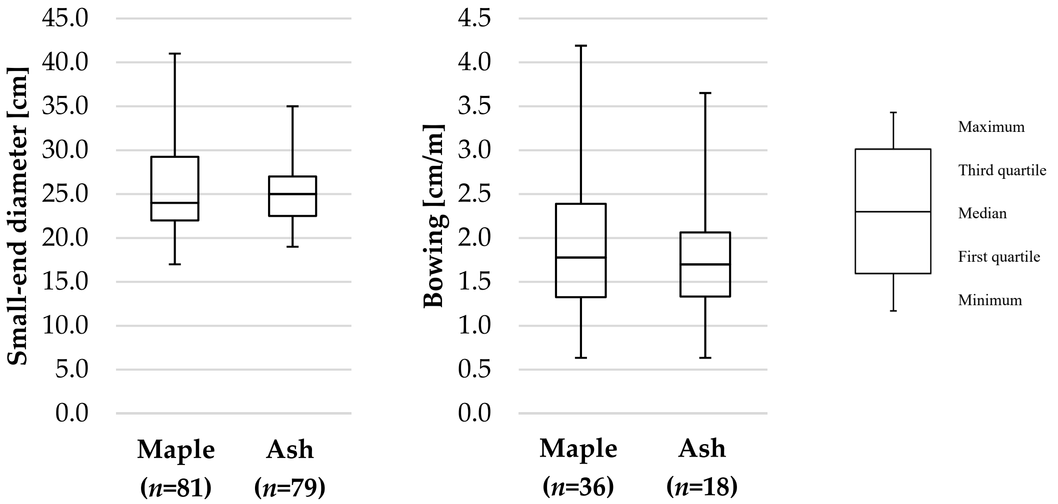

Figure 4. Boxplots for log section small-end diameter and bowing (only in one direction according to RVR instructions) separated after species (n = number of log sections).

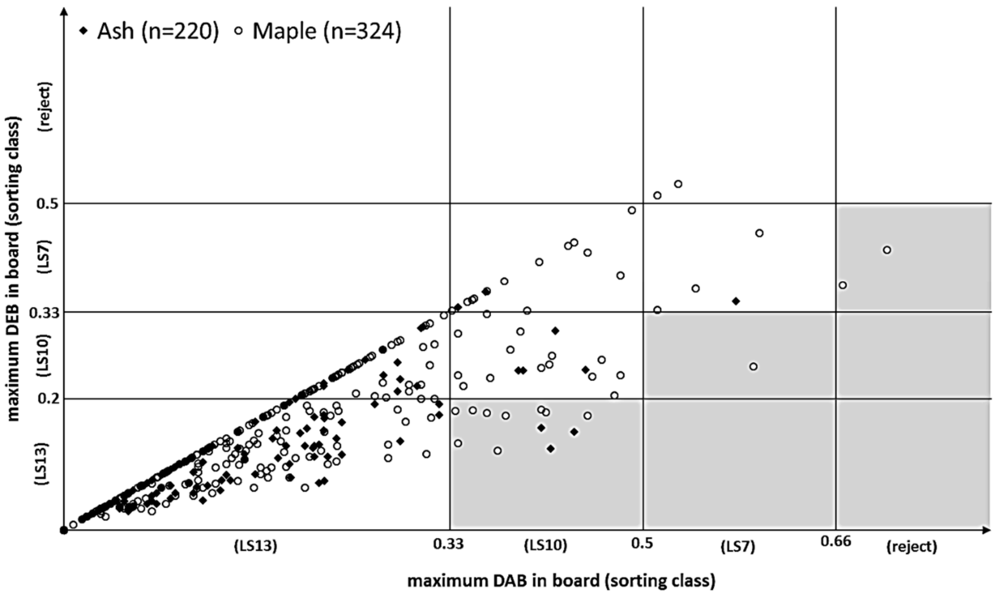

Figure 5. Maximum knot ratio of single knot (DEB) and knot cluster (DAB) for ash and maple boards. For all boards in grey area the criterion knot cluster (DAB) leads to downgrading into lower sorting class.

This confirms the findings made by other authors for the hardwood species beech. Frese and Riedler [38] postulate that for flat sawn beech lamellas (with lying annual rings) the sorting criterion DAB is not decisive for downgrading. Glos and Lederer [33] state that out of 219 beech boards only for one board the criterion DAB is sorting class determining. Blaß et al. [2] find similar results for a set of 350 beech boards (for 1.4% DAB decisive) and another set of 1888 beech boards (for 0.4% DAB decisive).

When applying stricter boundary values for the DAB than stated by the DIN 4074-5 [16], the DAB´s influence on the grade rises. In the combined grading proposed by Kovryga et al. [31], the boundary values for DEB and DAB for ash were set to be identical—i.e., the strictest DAB setting possible. Thus, 13.6% of the ash lamellas of this study are downgraded due to the criterion DAB (cluster knot). For maple grading according to the settings proposed by Kovryga et al. [31] only 6.5% of the studied lamellas are downgraded due to the criterion DAB (cluster knot). This is because the proposed DAB boundary values for maple are not as strict as for ash. Regarding knot clusters (DAB), Figure 5 suggests that the investigated maple wood contains proportionally more knot clusters than the ash wood. Further analysis reveals only a difference of 6%, though. A total of 33% of the ash boards and 39%

of the maple boards contain knot clusters (greater than the max. DEB). Figure 6 shows that these maximum knot clusters are bigger in the maple collective than in the ash collective. The same holds for single knots. This leads to a higher proportion of LS7 and LS10 boards in the maple collective compared to the ash group (see Figure 3).

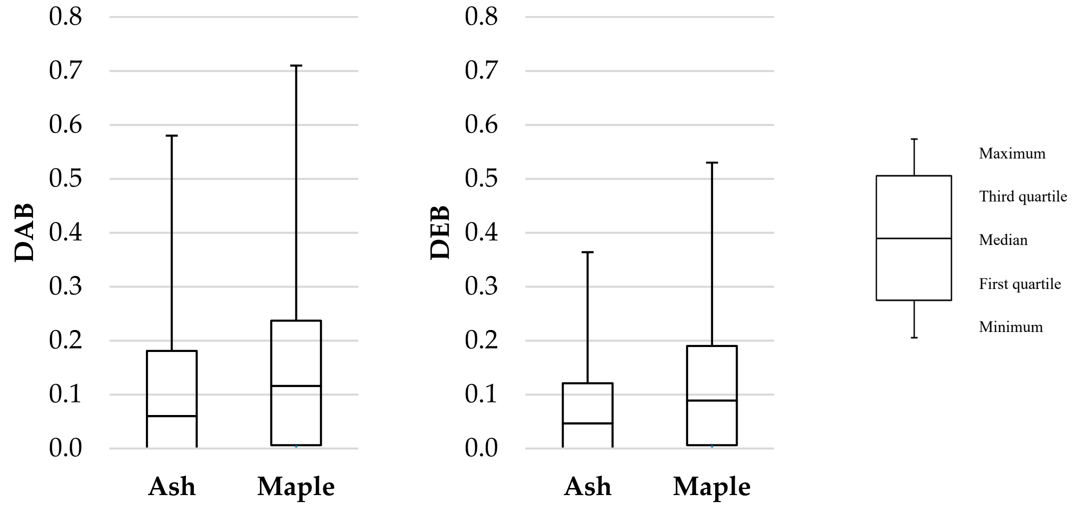

Figure 6. Boxplots separated after sorting criteria (maximum DEB and DAB in board) and species.

In general, special care must be taken when comparing grading results of different publications. The research material can be extremely diverse (i.e., species, origin, quality, sawing pattern, etc.), but also data acquisition for grading can be different. For example, Glos and Torno [28] grade the evaluated lumber only after the sorting criteria occurring within the tension test length, while for this study the entire board length is evaluated. Furthermore, the sorting criterion "grain angle" is a source of confusion, since its visual determination on unbroken boards is problematic [33,34].

5.3.2. Yields of Graded Lumber

The four sorting schemes presented in Figure 3 lead to different rates of so-called "rejects", i.e., boards that have to be sorted out. Table 8 lists the relative and absolute losses for the production step "grading" for each grading scheme and the resulting overall yields (referring to the round wood volume).

Table 8. Volume yields for the production step grading (from planed board to graded lamella) for four different grading schemes.

Product	Options for Production Step Grading	Maple				Ash			
		Yield		Waste/Loss		Yield		Waste/Loss	
		in m^3	in %	in m^3	in % PS	in m^3	in %	in m^3	in % PS
Boards planed (unsorted lamellas)		3.3	20.9			2.6	18.2		
	Grading I (Combined grading according to Kovryga et al. [31])			0.5	15.7			0.2	6.8
Combined grading lamellas		2.8	17.8			2.4	17.0		
	Grading II (4074-5)			1.3	39.0			1.3	49.8
4074-5 lamellas		2.0	12.7			1.3	9.1		
	Grading III (4074-5 without pith)			0.04	1.3			0	0
4074-5 lamellas without pith		3.3	20.6			2.6	18.2		
	Grading IV (4074-5, only DEB)			0.02	0.7			0	0
4074-5 lamellas (only DEB)		3.3	20.8			2.6	18.2		

When grading the lamellas according to DIN 4074-5 [16], for ash yield values lie around 9%, for maple around 13%. When excluding the sorting criterion "pith", total yields of ash are doubled (18.2%), those of maple rise to 20.6%. The difference between grading scheme III and IV is very little to none. This is due to the fact that the DAB (KC) has very little influence on the strength grading according to DIN 4074-5 [16].

As Table 8 shows, excluding the sorting criterion pith from the sorting scheme, raises the final yield considerably. Since board tension strength is the key influencing factor on glulam bending strength, tension testing of glulam lamellas has to show the effect the pith has on the board tension strength and stiffness (see [31]). If this influence is neglectable, the yield of grading can be raised extremely. It is important to state, though, that this does not hold equally for other strength properties. Glos and Torno [28], for example, prove for ash and maple that pith has a significant influence on the bending strength of square-edged lumber. They also stress the fact that the appearance of pith is often accompanied by bows, twists, and cracks. Similar results are presented by Glos and Lederer [33] for beech and oak square-edged lumber. Hübner [39] proves the pith's significant influence on the tension strength perpendicular to grain of ash glulam.

Further research has to work towards a hardwood strength grading system that is based on the mechanical properties of the resulting glulam. Kovryga et al. [31] proposes different optimized grading schemes for ash and maple glulam lamellas. For this study, one optimized combined grading solution from Kovryga et al. [31] was chosen for each species (see Table 3) to show an example of resulting yield. The chosen grading scheme distinguishes between three grades resulting in three board tensile strength classes based on destructive tension testing. For ash, the lowest class is DT22 with a characteristic tensile strength higher than 22 N/mm^2. For hardwoods, Kovryga et al. [40] proposes no tensile strength class lower than DT18. For lower mechanical properties softwood T-classes can be used. Therefore, for maple the lowest class is T15 (softwood tensile strength class) with a characteristic tensile strength not lower than 15 N/mm^2 (see Table 3). In this study, the proposed strength grading results in 15.7% rejects for maple and 6.8% rejects for ash. The resulting yields of 17.8% and 17.0% are considerably higher compared to grading according to DIN 4074-5 [16].

The economic feasibility of the production of hardwood glulam is strongly influenced by the final yield of glulam lamellas. Torno et al. [12] calculated that the production of beech glulam lamellas costs at least three times as much as that of spruce lamellas, calculating with beech round wood prices of €53.50–€80.00 per cubic meter. Since final yield figures of this study and Torno et al. [12] lie in a similar range, these costs can also be assumed for the lamellas of this study. This makes raising the yield inevitable, if a competitive hardwood product shall be produced.

When evaluating the competitiveness of a product, not only the production cost, but also the added value should be considered. Following the proposed combined grading of Kovryga et al. [31], for this study strength classes with a characteristic tensile strength as high as 38 N/mm^2 can be produced. With ash lamellas of this characteristic strength, glulam with bending strength values of as high as 48 N/mm^2 can be achieved [4]. Via "upgrading", i.e., cutting out large knots, the characteristic tensile strength of ash lamellas can be raised up to 54 N/mm^2 [31]. Using the combined grading approach for beech lamellas, Erhardt et al. [41] report tensile strength values of as high as 50 N/mm^2. This raised strength allows the production of more slender structures, which means material savings but also more construction possibilities for the architect and engineer. The listed benefits would yield obviously in higher reward for the producer. Although the present market situation has not led to a wide spread use of hardwood glulam, future changes in spruce availability, round wood prices (especially hardwood) and wood processing technology (etc.) might make the production lucrative.

6. Conclusions

For this study, the volume yields of the production of glulam lamellas from low quality and low dimension ash and maple log sections are investigated. For this purpose, 16.25 m^3 of maple (81 log sections) and 14.89 m^3 of ash (79 log sections) were harvested from natural forest stands (mixed beech forests) in central Germany and were turned into dry-dressed lumber (unsorted lamellas) with state of the art technologies. The resulting board volumes amount for only 20.9% (maple) and 18.2% (ash) of the original log volumes. The most waste is produced in the production step "presorting and planing" (maple: 56%; ash: 60%), since here a high percentage of the boards has to be sorted out due to bowing. By trimming these boards to shorter lengths, the waste of this production step could be reduced considerably. In addition, the sawing (milling) of the boards produced in both cases around 50% waste, which is in line with the above-mentioned literature values for sawing low-quality hardwoods. Nonetheless, with an adjusted sawing technology, this waste can be reduced (e.g., through shorter log sections and optimized machine combinations). It is also advisable to define a minimum input log diameter, since the lower the log diameter is, the lower the volume yield of milling becomes. Another approach to a raised final volume and value yield is the diversification of final products. Thus, as an example, glulam lamellas could be produced as a low-quality co-product from the production of high quality lumber for furniture production.

Strength grading of lamellas lowers final volume yields even further. When sorting the lamellas according to DIN 4074-5 [16], final volume yields of 12.7% for maple and 9.1% for ash are attained. One way of raising the final volume and also value yield could be the adjustment of the sorting (grading) scheme. For example, by excluding the criterion "pith" from sorting, final yield values of 20.6% (maple) and 18.2% (ash) can be achieved. Generally, it is advisable to combine visual and machine sorting to an assortment and species adjusted combined grading, which is optimized after the criteria "desired tensile strength and stiffness" but also "yield". The paper Kovryga et al. [31] is attempting this. Resulting total yields, when applying the selected optimized combined grading of Kovryga et al. [31] to this study´s lumber, lie between 17% and 18%. This yield is considerably lower than that obtained for softwood glulam lamellas. Factors like the higher attainable tensile strength, if compared to 30 N/mm^2 possible for softwoods [42], and the appealing appearance of hardwood glulam may make up for the yield disadvantages. In general, the economic feasibility of hardwood glulam is influenced by a serious of factors, which have to be analyzed in detail for each final product and production plant separately.

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References

1. Sauter, U. WP 1: Hardwood Resources in Europe—Standing Stock and Resource Forecasts. Presented at Workshop "European Hardwoods for the Building Sector", Garmisch-Patenkirchen, Germany, 2016.
2. Blaß, H.J.; Denzler, J.; Frese, M.; Glos, P.; Linsenmann, P. *Biegefestigkeit Von Brettschichtholz Aus Buche [Bending Strength of Beech Glulam]*; Karlsruher Berichte zum Ingenieurholzbau, Band 1 Karlsruher Berichte zum Ingenieurholzbau; Universitätsverlag Karlsruhe: Karlsruhe, Germany, 2005.
3. Frühwald, A.; Ressel, J.B.; Bernasconi, A.; Becker, P.; Pitzner, B.; Wonnemann, R.; Mantau, U.; Sörgel, C.; Thoroe, C.; Dieter, M.; et al. *Hochwertiges Brettschichtholz Aus Buchenholz [High Quality Glulam Made of Beech Wood]*; Final Report; University of Hamburg: Hamburg, Germany, 2003.
4. Van de Kuilen, J.W.; Torno, S. *Materialkennwerte von Eschenholz Für Den Einsatz in Brettschichtholz [Material Properties of Ash Wood for the Use in Glulam]*; Final Report; Holzforschung München, Technische Universität München: Munich, Germany, 2014.
5. DIBt. BS-Holz aus Buche und BS-Holz Buche-Hybridträger [Glulam and hybrid glulam made of beech]; German technical building approval Z-9.1-679; holder of approval: Studiengemeinschaft Holzleimbau e.V., Germany; issued by Deutsches Institut für Bautechnik (DIBt), Germany; valid until 27.10.2019. 2014.

6. OiB. VIGAM—Glued laminated timber of oak; ETA-13/0642 European Technical Approval; holder of approval: Elaborados y Fabricados Gámiz, S.A., Spain; issued by Austrian Institute of Construction Engineering (OiB), Austria; valid until 27.06.2018. 2013.
7. DIBt. Holz Schiller Eiche-Pfosten-Riegel-Brettschichtholz [Timber Schiller oak post and beam glulam]; German technical building approval Z-9.1-821; holder of approval: Holz Schiller GmbH, Germany; issued by Deutsches Institut für Bautechnik (DIBt), Germany; valid until 02.03.2018. 2013.
8. OiB. Sierolam—Glued laminated timber of chestnut; ETA-13/0646 European Technical approval; holder of approval: Siero Lam, S.A., Spain; issued by Austrian Institute of Construction Engineering (OiB), Austria; valid until 27.06.2018. 2013.
9. Mack, H. The European Market for Glulam—Results of a Survey within the European Glued Timber Industry. In Proceedings of the "Wiener Leimholz Symposium 2006", Vienna, Austria, 23–24 March 2006; pp. 35–50.
10. Ohnesorge, D.; Hennig, M.; Becker, G. Bedeutung von Laubholz bei der Brettschichtholzherstellung [Significance of hardwoods in glulam production]. *Holztechnologie* **2009**, *6*, 47–49.
11. Welling, J. Differences between hard—and softwoods and their influence on processing and use. In Proceedings of the "Gülzower Fachgespräche Stoffliche Nutzung von Laubholz", Würzburg, Germany, 6–7 September 2012.
12. Torno, S.; Knorz, M.; Van de Kuilen, J.W. Supply of beech lamellas for the production of glued laminated timber. In Proceedings of the 4th International Scientific Conference on Hardwood Processing, Florence, Italy, 7–9 October 2013; pp. 210–217.
13. Wiedenbeck, J.; Scholl, M.S.; Blankenhorn, P.R.; Ray, C.D. Lumber volume and value recovery from small—diameter black cherry, sugar maple, and red oak logs. *BioResources* **2017**, *12*, 853–870. [CrossRef]
14. Lin, W.; Wang, J.; Wu, J.; DeVallance, D. Log Sawing Practices and Lumber Recovery of Small Hardwood Sawmills in West Virginia. *For. Prod. J.* **2011**, *61*, 216–224. [CrossRef]
15. Van de Kuilen, J.W.; Torno, S. *Untersuchungen Zur Bereitstellung von Lamellen Aus Buchen- Und Eschenholz Für Die Produktion von Brettschichtholz [Studies on the Supply of Lamellas for the Production of Glulam from Beech and Ash Wood]*; Final Report X37; Holzforschung München, Technische Universität München: Munich, Germany, 2014.
16. DIN 4074-5. *Strength Grading of Wood—Part 5: Sawn Hardwood*; German Institute for Standardization (DIN): Berlin, Germany, 2008.
17. Ehlebracht, V. Untersuchung Zur Verbesserten Wertschöpfung Bei Der Schnittholzerzeugung Aus Schwachem Buchenstammholz (Fagus Sylvatica L.) [Investigation on improved Added Value in the Production of Sawn Lumber from Low Dimension Beech Timber]. Dissertation, Georg-August-Universität Göttingen, Göttingen, Germany, 2000.
18. Eickers, A. Verschnittuntersuchungen Bei Der Verarbeitung von Brettschichtholzlamellen [Yield Loss in the Production of Glulam Lamellas]. Diploma Thesis, Fachhochschule Hildesheim/Holzminden, Hildesheim, Germany, 1997.
19. Steele, P.H. *Factors Determining Lumber Recovery in Sawmillin*; General Technical Report FPL-39; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 1984.
20. Richards, D.B.; Adkins, W.K.; Hallock, H.; Bulgrin, E.H. *Lumber Values from Computerized Simulation of Hardwood Log Sawing*; Research Paper FPL-356; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 1980.
21. Emhardt, M.; Pfingstag, S. *Schnittholzqualität und Ausbeute von Schwachem Buchenstammholz [Sawn Lumber Quality and Yield Produced from Low Dimension Beech Logs]*; Final Report; FVA Baden-Würtemberg: Freiburg, Germany, 1993.
22. Fronius, K. *Arbeiten Und Anlagen Im Sägewerk—Spaner, Kreissäge, Bandsäge [Work and Machines in a Sawmill—Chipper Canter, Circular Saw, Band Saw]*, 2nd ed.; DRW-Verlag Weinbrenner: Leinfelden-Echterdingen, Germany, 1989.
23. Fischer, H. *Neue Verwendungsmöglichkeiten von Laubschwachholz [New Possible Uses for Low Dimensions Hardwood Timber]*; Internal Report; Forstliche Versuchsanstalt Rheinland-Pfalz: Trippstadt, Germany, 1996.
24. Lamb, F.M.; Wengert, E.M. Techniques and procedures for the quality drying of oak lumber. In Proceedings of the 41st Meeting of the Western Dry Kiln Association, Corvallis, OR, USA, 1990.
25. Denig, J.; Wengert, E.M.; Simpson, W.T. *Drying Hardwood Lumber*; General technical Report FPL-GTR-118; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2000.

26. Kollmann, F.; Côté, W.A., Jr. *Principles of Wood Science and Technology, I. Solid Wood*; Springer: Berlin, Heidelberg, 1968.
27. Wagenführ, R. *Holzatlas*; Fachbuchverlag im Carl Hanser Verlag: Leipzig, Germeny, 2007.
28. Glos, P.; Torno, S. *Aufnahme Der Einheimischen Holzarten Ahorn, Esche und Pappel in Die europäische Norm EN 1912: "Bauholz – Festigkeitsklassen— Zuordnung von Visuellen Sortierklassen und Holzarten" [Inclusion of tha Native Wood Species Maple, Ash and Poplar in the European Standard EN 1912: "Structural Timber—Strength Classes—Assignment of Visual Grades and Species"]*; Final Report 06517; Holzforschung München, Technische Universität München: Munich, Germeny, 2008.
29. RVR. *Rahmenvereinbarung Für Den Rohholzhandel in Deutschland (RVR) [Framework Agreement on Raw Timber Trade in Germany]*; Deutscher Forstwirtschaftsrat & Deutscher Holzwirtschaftsrat: Berlin, Germany, 2015.
30. DIN 1316-3. *Hardwood Round Timber—Qualitative Classification—Part 3: Ash and Maples and Sycamore*; German Institute for Standardization (DIN): Berlin, Germany, 1997.
31. Kovryga, A.; Schlotzhauer, P.; Stapel, P.; Militz, H.; Van de Kuilen, J.W. Visual and machine strength grading of European ash and maple for glulam application. *Holzforschung* **2019**, *0*. [CrossRef]
32. Hankinson, R.L. *Investigation of Crushing Strength of Spruce at Varying Angles of Grain*; Air Service Information Circular No. 259; U.S. Air Service: Washington, DC, USA, 1921.
33. Glos, P.; Lederer, B. *Sortierung von Buchen-Und Eichenschnittholz Nach Der Tragfähigkeit Und Bestimmung Der Zugehörigen Festigkeits-Und Steifigkeitskennwerte [Strength Grading of Beech and Oak Lumber and Determination of Characteristic Strength and Stiffness Values]*; Final Report; Institut für Holzforschung, Technische Universität München: Munich, Germany, 2000.
34. Frühwald, A.; Schickhofer, G. Strength grading of hardwoods. In Proceedings of the 14th International Symposium on Nondestructive Testing of Wood, Eberswalde, Germany, 2–4 May 2005.
35. Frese, M.; Blaß, H.J. Beech glulam strength classes. In Proceedings of the Meeting 38 of the International Council of Research and Innovation in Building and Construction, Working Commission W18—Timber Structures, Karlsruhe, Germany, 2005.
36. Wade, M.W.; Bullard, S.H.; Steele, P.H.; Araman, P.A. Estimating Hardwood Sawmill Conversion Efficiency Based on Sawing Machine and Log characteristics. *For. Prod. J.* **1992**, *42*, 21–26.
37. Torno, S.; Van de Kuilen, J.W. Esche für tragende Verwendungen—Festigkeitseigenschaften visuell sortierten Eschenholzes [Ash for load bearing use—Strength properties of visually graded ash lumber]. *LWF Aktuell* **2010**, *77*, 18–19.
38. Frese, M.; Riedler, T. Untersuchung von Buchenschnittholz (Fagus sylvatica L.) hinsichtlich der Eignung für Brettschichtholz [Examination of suitability of beech lumber for glulam]. *Eur. J. Wood Wood Prod.* **2010**, *68*, 445–453. [CrossRef]
39. Hübner, U. Mechanische Kenngrößen von Buchen-, Eschen- Und Robinienholz Für Lastabtragende Bauteile [Mechanical parameters of Beech, Ash and Locust Lumber for Load Bearing Members]. Ph.D. Thesis, Technische Universität Graz, Graz, Austria, 2013.
40. Kovryga, A.; Stapel, P.; Van De Kuilen, J.W. Tensile strength classes for hardwoods. In Proceedings of the 49th INTER & CIB Meeting, Graz, Austria, 2016.
41. Erhardt, T.; Fink, G.; Steiger, R.; Frangi, A. Strength grading of European beech lamellas for the production of GLT & CLT. In Proceedings of the 49th INTER & CIB Meeting, Graz, Austria, 2016.
42. EN 338. *Structural Timber–Strength Classes*; European Committee for Standardization: Brussels, Belgium, 2016.